A STUDY OF THE EFFECTS OF BIAXIAL STRESS AND LOW TEMPERATURE ON THE FAILURE OF MILD STEEL CYLINDERS

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"A Study of the Effects of Biaxial Stress and Low Temperature on the Failure of Mild Steel Cylinders"

A Thesis Submitted to the

Faculty of Webb Institute of Naval Architecture

In Partial Fulfillment of

the Requirements for the Degree of Master of Science

in

Naval Architecture and Marine Engineering

by

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ACKNOWLEDGEMENTS

The authors wish to thank Rear Admiral R.T.Cowdrey, USN, Commander of the New York Naval Shipyard, and Captain H.T. Koonce,USN, Director of the Material Laboratory, for the use of the facilities of the yard and laboratory.

We also wish to thank the following people for their very valuable help, criticism, and consul:

Mr. M.J.Berg
Mr. K.R.Mercy
Mr. H.V.Cordiano
Mr. C.K.Chatten
Mr. E.R.Lewis
Mr. J.J.Nicolette
Mr. F.J.Sidnam
Mr. J.E.Russell
Mr. A.A.Booth
Mr. C.Ridgely-Nevitt
Mr. W.R.Jensen

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SUMMARY

Investigations of the ship's failure problem have been approached from just about every angle and work has been going on for well over a decade om this serious problem. Why do merchant ships crack in half? At first the answer was easy- it was because of welding,for these were the first ships to experience such a phenomenon and these were the first welded ships. Now-a-days the answer given above doen't hold. Corrective measures have been taken and still ships flounder and break in two.

We hope in this investigation to approach the problem from a new angle and at leabt start to answer the question "why?". Please note that we are not trying to determine an acceptance test for steel ncr are we trying to find corrective measures in present day ship construction. We are merely trying to throw light on a strange phenomenon.

Involved in the failure of steel are many conditions. One of these is the method of stress loading,ie: uniaxial, biaxial, or triaxial. We have selected the biaxial pattern.

In order to obtain this pattern in such a manner that we could control the ratio of the two stresses, we used a seamless cylindrical tube of structual steel, mounted in ends which are attached to the tensile testing machine. By pulling we introduce the axial stress. By introducing hydraulic pressure into the pipe we are able to apply the second stress, the hoop stress, thus giving us the biaxial stress pattern. The ratio of the axial stress to the hoop stress is known as the

stress ratio which we are capable of setting at any given value. Thus we have our first variable-stress ratio.

The second variable that we introduce is temperature. This was introduced because many of the ship failures occurred at below normal temperatures.

From previous examinations and observations of actual failures it has been proven that brittle fractures exsisted. A brittle fracture is a fracture where there has occured little or no permanent reduction in cross sectional area or no elongation. Using temperature as a variable the transition temperature has been defined as that temperature at which a material exhibits a transition from the ductile to the brittle failure. This temperature by its very nature covers a wide range and is dependent upon the type test the material is subjected to.

We hope to see what effect the varying of the stress ratio has on obtaining a brittle fracture with varying temperature. This is our objective projected into the future. In the short time which we have available we could only hope to obtain a suitable set-up in order that another group could continue the test and obtain the results.

We have, we believe, perfected the system so that this experiment can be carried out with the minimum of set-up time and trouble. On the whole seven different methods of specimen attachment were tried before we obtained a suitable one. We were able to obtain a brittle fracture,a ductile fracture, and obtained any desired stress ratio and temperatures down to fifty four degrees below zero fahrenheit.

INTRODUCTION

Since 1942 approximately 165 welded merchant ships (6) have experienced structural failures in the form of brittle failures or fractures at stresses below the ultimate strength of the steel that is shown by the ordinary tensile testing methods. A large number of these failures have occured during heavy weather and at near freezing temperatures. The literature concerning the investigations of these failures and the research work done concerning the problem of ship failure has shown some very interesting results which will be discussed below.

A new term has been introduced which is called the"transition temperature". It is generally defined as the temperature above which the steel exhibits failure in a ductile manner and below which steel fails in a brittle manner. It generally is given as a range of temperature rather than a single value because of the very nature of the transition. A steel with a low transition temperature is to be preferred to one with a high transition temperature because a structure built with a steel having a high transition temperature would be operating in the brittle range. Most structures built do not operate in the extremely low temperature ranges and hence the structure is given a factor of safety by virtue of this factor alone even though the limiting low service temperature may not be known exactly.

The metallurgical history of the metal has a definite effect on the behavior of the metal. The composition of the

metal : in particular the amount of carbon, manganese, aluminum, vanadium, phosphorus, and nickle and their homogeneity or distribution throughout the specimen have an effect on the ultimate strength, the notch sensitivity, the strain aging, and the fatigue strength of the metal. These factors are all intimately related and are extremely intangible in so far as their application to practical problems are concerned. It would be an extremely difficult problem to set design criterion for them since one could never tell the state of fatigue in a particular member of a structure as complicated as a ship. Work to determine the comparative qualities for various composition steels along these lines has been done by many investigators. The Izod, Charpy, and the Navy Tear Test have been used to determine the notch sensitivity and transition temperature. Fatigue test, strain aging, and accelerated corrosion test have been run on various composition steels of various shapes as regards the specimens, to determine the notch sensitivity, the fatigue limit and other effects. The methods used seem to be adequate to determine the relative qualities of the various steels. When the best steels that are economically feasible are determined these are the steels to use. The heat treatment that the steel receives has a definite effect of the final grain size. Large grain sizes are to be avoided if possible since they have an adverse effect on the notch sensitivity of the metal. Oil or water quenching gives the smallest, normallizing the next smallest, and annealing the largest grain size.'

Various mechanical factors have an effect on the metal.

Welding changes the grain size and introduces locked in stresses and residual stresses along with those introduced by the method of fabrication or assembly. The determination of these stresses and effects in actual practice would be impractical if not impossible. It should be appreciated that these stresses can complicate the picture and give a condition of biaxial or triaxial stress when only uniaxial stress might be expected. Workmanship, proper sequence of assembly and welding should be given very careful attention.

Almost any discontinuity will introduce a stress concentration. A series of stress concentration factors have been worked out for certain geometrical shapes by such methods as photoelasticity. If stress concentration factors are to be used in design they should be applied to those discontinuities which are designed into the ship. If we were to use the stress concentration factor for an infintestmal crack such as might appear in a weld our design would soon get out of proportion.

Size effect has been investigated and it has been noted that for the same composition steel different transition temperatures have been noted and different relative notch sensitivities, fatigue strength, etc., have been obtained for different size specimens. Size effect generally appears because it gives a gradient of stress in the specimen. It introduces restraint as the size increases and increases the severity of triaxial stresses. In most structual members a condition of multiaxial stress exists which raises the transition temperature of the steel.

Plastic deformation even at room temperature before rupture is much less for biaxial or triaxial stress than for one way stress and for this reason metals that are ordinarily ductile may prove brittle when thus stressed. It has been shown that at elevated temperatures the tendency for most metals to creep or flow at a stress less than the short time yield stress or ultimate strength is greatly increased and makes neccessary the selection of a working stress which will cause neither excessive deformation or rupture. Since the temperature of the metal has an effect on the properties of the metal at elevated temperatures it is possible that it also has an effect at low temperatures. Stresses are also introduced by temperature differences in the structure.

Brittle failure can be induced by a very high strain rate. If plastic flow in a failure is low, the restraint high, brittle failure can occur at much lower strain rates. The loss of effective area raises the overall stress level as the crack progresses.

Thermal stresses due to temperature differences, residual stresses, hydrostatic and deck loads, vibration and shock in a sea-way, discontinuities with their stress raising effects , multiaxial stress nature and stress gradients, added to the complex nature of a ships structure actually gives a state of multiaxial stress rather than a uniaxial stress as assumed in ordinary calculations.

Since it is impossible to investigate the entire structure of a ship, but it is possible to evaluate the parts separately

to a certain extent, it would be desirable to know the effects of various stress ratios at various temperatures.

To investigate the problem it is proposed that at varying temperatures seamless tubular specimens, machined to size, be tested to failure at a fixed stress ratio. At the lowest temperature available the tension and the internal pressure will be increased in uniform steps and observations will be made to see if brittle failure occurs. If it does, then the temperature will be raised and another test run at the same stress ratio. This procedure will be followed in a manner designed to bracket the transition temperature of the specimen.

Experimental information indicates that the effects of hydrostatic pressure on the stress strain curve is small, a second order effect that need be considered only occasionally. The tube wall should not be too thin; still the ratio of the wall thickness to radius of the specimen should be kept small to keep the third principal stress small so that the case may be considered one of biaxial stress. Since the yield point of the specimen depends greatly on the prior history of stressing of the specimen the same test procedure will be used on all specimens.

For the determination of the pressures and tensions to be used to keep the stress ratio constant during the test procedure the specimen will be considered to be a thin wall cylinder with closed ends and the following formulas will be used in the computations (3):

$$\sigma_1 = \left(p d_p^2 + \frac{4P}{\pi}\right) / 4 t_p (d_p + t_p) \qquad \sigma_2 = \frac{p d_p}{2 t_p}$$

where - "p" is the internal pressure in pounds per square inch

"P" is the total axial load in pounds

"t_p" is the actual wall thickness in inches

"d_p" is the actual internal diameter in inches.

Strain gauges will be used to give a check on the stress ratio as the test proceeds and to give a plot o f the principal stresses against the principal strains. While a plot of the information beyond the elastic limit would be desirable the problem of strain gauging would become too complex. We are after brittle breaks and the record of the internal pressure and tension during this portion of the test and an accurate determination of the scantlings of the specimen after the break should give accurate information concerning the fracture stresses. In the case of a complete brittle fracture there should be no appreciable permanent flow of the metal. From the literature if there is any shear fracture at all, the fracture should be preceeded by a short period of local bulging or necking down combined with a local decrease of thickness when either the total axial load or the internal pressure reaches a maximum value. The escape of the oil when the crack first starts may cause some tearing of the metal in the vicinity of the crack.

From the slope of the stress versus strain curves the value of the modulus of elasticity of the metal "E" can be determined by measuring the slope of the curve toward the strain axis.

For plotting purposes the Henky-von Mises plot will be used to give the required two dimensional representation of

the conditions at failure of the metal. Normally a metal can fail in two ways; by flow of the metal when the stresses pass or exceed the yield point of the metal, or the metal can fracture. Normally the above plot is based on the yield strength of the metal but we will use it with the ultimate strength of the metal. This plot includes all the principal stresses or strains as variables and gives an accurate picture of the conditions at failure of the specimen. In our calculations the third principal stress which is the radial stress or the direct stress caused by the hydrostatic pressure will be neglected since its magnitutde will be a maximum of four to five thousand pounds per square inch. The following formulas (4) will be used for the plot:

$$\sigma_u = \sqrt{\sigma_1^2 + \sigma_2^2 - \sigma_1 \sigma_2}$$

σ_u = ultimate tensile stress

σ_1 = axial stress

σ_2 = hoop stress

PROCEDURE

The specimens obtained were 2.860" outside diameter, 2.611" inside diameter, mild steel pipes which were of the same seamless variety. All the specimens run in this series of test were from the same mill lot. A complete metallurgical report on the steel in the specimens is contained in the appendix.

The specimens were cleaned by placing them in a half barrel of boiling caustic solution and removing the preservative. The specimens were then wire brushed inside and out. The specimens were heated to a cherry red and allowed to anneal before machining to insure that the amount of cold working that each specimen had received would be the same. The specimens were then wire brushed again inside and out to insure a clean surface.

Various shape specimens were tried and are listed below. The final test specimen shape decided upon is shown in Fig.(2).

(a) an unturned specimen eighteen inches long-this was discarded due to the limited capacity of the pressure pump and the tensile test machine.

(b) an eighteen inch long specimen with a center test section ten inches long turned to a diameter of 2.800". The ends of the test section were turned to a radius to avoid a notched corner.

(c) same as above but with a five-eigth inch long groove one half inch from each end turned to a diameter of 2.840" to receive a tapered wedge.

(d) same as above but with a smaller test section four inches long turned to a diameter of 2.775" in addition to the

ten inch section. This was the final specimen used and is shown in Figure (2).

To turn the specimens, they were mounted in two special end plugs designed to slide into the ends of the pipe and to be a tight firm fit. The specimens were turned between centers on a 30" swing American "Pacemaker" lathe. The specimens were turned with a round nose finishing tool in the test section. The grooves were rough cut with the round nose finishing tool and finished to a sharp corner with a right and left hand facing tool. By using the speeds and feeds shown in the table below it was possible to rapidly turn the specimens and to avoid such pitfalls in turning hollow thinwalled specimens as chatter and whipping.

CUT	RPM	FEED	DEPTH OF CUT
roughing cut 16"sect	228	.007"	.025"
finishing 10"sect	370	.003-4"	.010"
roughing 4"sect	228	.005"	.020"
finishing 4"sect	370	.002"	.005"
grooving	228	.004"	.010"

After the specimens were turned they were polished with 3/0 emery paper and then with steel wool to remove any notches. The finishing tool was specially ground to maintain a smooth radius at the terminal ends. The facing tools were used to finish the grooves to give a square edge to provide a solid seat for the wedges. When the specimens were finished they were again cleaned with a wire brush and kerosene and wiped dry preparatory to mounting them.

For historical purposes only, the following is a list of of the methods of attaching or mounting the specimens for testing that were tried. The last named method is the one that proved satisfactory.

(a) silver soldering the pipes to plugs which fit inside the pipe.

(b) sweat brazing the pipes to the same plugs.

(c) welding the pipes to the plugs

(d) using the split collar method of attachment with the collar bearing on a welded bead on the ends of the pipes and bolted to a top plate which is fitted to attach to the cross heads on the tensile testing machine.

All the above methods involved heating of the specimen in an irratic manner and an uncontrollable manner which we felt would introduce a variable which might spoil any results which we might get. The last two mentioned methods worked.

(e) using tapered collars with a $1\frac{1}{2}$ degree taper chinching up on split ring wedges which fitted on the specimen. There was a plug which fitted inside the specimen to back up the wedge and onto which the tapered collars were screwed.

(f) same as above but with a groove machined into the ends of the specimen to hold the wedges in place.

Both of these methods worked but were irratic in their behavior and the broken specimens were hard to remove due to the tremendous forces set up by the small taper. The wedges were first cut into three sections and glued on with "Duco" cement, then with "Epon" cement. Neither of these methods worked

very successfully, the wedges canted, the "Epon" cracked at low temperatures and, in general, were unsuccessful. The wedges were then turned, annealed to stress relieve them, and split ~~only~~ once like a piston ring. This stopped the wedges from canting and improved the system, but the finished specimens were still difficult to remove.

(g) same as the last specimen described but with a five degree taper. This method worked, was reliable, and was easy to disassemble.

Refering to Figure(6) and the description of the parts the test specimen is mounted as follows:

Put one wedge in place in its groove remembering to have the taper set with the small end toward the center of the specimen. Attach the leather pressure cups to the ends of the plugs by use of the disc and the two machine screws making sure that the leather cups are first cleaned in kerosene and then coated with oil. Then, with the use of the Baldwin-Emery Tensile Test Machine press one plug into the pipe at the end of the pipe which has the wedge attached. The pipe should ride on the plug up to the curved radius or to 10,000 pounds load. Be sure not to bell the pipe by forcing the plug too far or you will have trouble screwing the collars on and in removing the wedges after the specimen is broken. Turn the pipe around and drop on both of the collars with both small ends of the tapers facing toward the center of the specimen. At this point put on the second wedge and insert the assembled plug in the open end of the pipe and repeat the above procedure for pressing. While there is still

a load on the machine screw the two collars down hand tight. With the aid of the $4\frac{1}{2}$" wrench, turn the collars down until they catch the wedges and get fairly tight. The assembly is now ready to mount in the machine. All parts of the collar assembly should be well greased with light oil and silicone grease before they are assembled. The threads should be cleaned with a brush to remove any particles of dirt or grit that might jam the threads as the collars are set up.

To remove the plug and collar assembly after the specimen is broken, remove the assemblies from the universals on the machine and remove the pipe fittings. Set the collars in the power hack-saw and saw the pipe one half inch from the ends of the ten inch test section. Remove the leather cup assemblies and then set the ends up in the test machine for compression. Load the machine at a steady rate until there is a distinct pop and the load goes off. This is an indication that the wedges have been unseated. With the load set at about 2500 pounds unscrew the collars. Remove the ends from the machine. Set the ends in a vise horizontally so that the jaws are gripping the remaining pipe section after the wedges have been removed. You can now use a solid steel bar to ram the plugs out of the pipe ends. The collar assemblies have to be cleaned then they are ready for reassembly.

The collar assembly marked #2 goes up and the whole unit is mounted into the universals of the machine. On the bottom of the lower plug is a pipe fitting for attaching the oil line from the oil pump. This fitting should be screwed on to the plug

before the plug is put into the lower universal. When the oil connection is completed , the system is ready for filling with oil. The oil used is a light hydraulic oil. Care must be used when filling the pump ~~resivior~~ reservoir since any partical of dirt or grit can damage the polished parts of the pump and its pressure seal cup and non-return valves. With someone watching the hole in the top plug which vents the system, pump the oil until clear oil is seen coming out of the top. This means that all the air is out of the system. Close off the top hole with the machine bolt furnished which acts as a plug. At this point the system is assumed to have had the strain gauges attached, an operation to be described next. After clearing the strain gauges and wires and attaching the thermocouple wire to the specimen by means of scotch tape and covering it with molten wax, the system is assumed to have had a check to see that none of the wiring is shorted out, the refrigerator box is attached and the system is ready for running.

At the offset of this investigation it was felt that the use of strain gauges was necessary to establish certain patterns. It must be realized that their use is limited to within the elastic range where a value of the modulus of elasticity "E" is known. For continuation of the investigation the authors feel that the use of strain gauges is unnecessary. Since all test are run to destruction, the gauges fail at the elastic limit, and strain values below this limit are of little concern. The discussion that follows is the procedure that we used to attach the gauges and the experience and imformation gained.

Since one of the variables in the series of experiments is the stress ratio, a definite means had to established for determining these ratios, and, once obtained, for holding them throughout the test run. We were not sure that our system could do this so strain gauges were attached to be a definite check on our system. One of the biggest fears we had was that the use of the equations for axial and hoop stress in the pipe taken from mechanics of material would not give accurate enough information. Strain gauges would give us the needed proof at all values of the stress ratio up to the elastic limit which in some cases we expected to be almost to the end of the run.

Theory demanded that bending be eliminated from our test results and this was accomplished by placement of the gauges in series. Four gauges were used, two sets of two gauges, each set in series, two horizontal 180 degrees apart, and two vertical 180 degrees apart and 90 degrees from the other pair at the center of the four inch test section. In this way any bending stresses which might be introduced by the method of attachment and testing were cancelled out. The location of the gauges on the specimen is assumed to be satisfactory for the imformation desired.

By use of the strain gauges other pertinent imformation was obtained, ie, the modulus of elasticity "E" and the elastic limit. In the determination of the modulus, a sample pipe was taken, and by using only axial tension and its stress versus strain curve, and measuring the slope or using the known cross sectional area, "E" was found to be ~~30.6~~ 28.5 x 10^6 lbs/ square inch.

Recording of the reading was done by the use of a Type "K" Baldwin Strain Gauge Indicator.

The refrigeration system consist of a variable speed AC blower which is insulated & insulated three inch ducting leading to a refrigerator box which is shelved and ducted to receive the air from the blower and pass it over the shelves on which is placed dry ice. From the refrigerator box, three inch insulated ducting leads the air to a cylindrical shaped specimen box which is also packed with dry ice. The box is designed to spirally circulate the air around the specimen and then to discharge it through the same type ducting back to the inlet of the blower. The refrigeration system is essentially a closed recirculating dry ice and air system. The walls of the refrigerator box and test specimen enclosure are one inch thick insulating material covered with sheet metal on both sides. The joints are made by crimping and soldering. The refrigeration system is shown in Figure (14).

The hydraulic system consists of the pump system of a Navy Guided Bend Test Machine which is capable of delivering pressures up to five thousand pounds per square inch. The piping used is extra strong quarter inch piping. A light grade of hydraulic oil was used in the system. The system is shown in Figure (14).

The pressure cups that were inserted in the system in the test specimens as shown in Figure (9) were made by use of a formed male die and a four inch section of test pipe to act as the female die. The leather used was one-eighth inch thick.

A circular piece of leather was cut to size and then soaked in water at one hundred and forty degrees fahrenheit to soften it. After the leather was soft, the dies were pressed together and allowed to set for twenty four hours. When the cups were removed from the dies, they were hard and stiff and the edge was feathered by means of a razor blade and sanding. After the cup was formed and the attachment holes drilled, the cups were softened by soaking them in hydraulic oil and working them with the hands. They were then attached to the plugs by means of the washers and machine screws.

RESULTS

A brief resumé of the results of a series of nine tests is given in tabular form below. Detailed results ~~nad~~ and calculations for each test, along with the temperature vs time plot and the thermocouple constants are included as the main section of the appendix.

Test No.	Date	Temp. deg F	S.R.	S.R. Failure	Tensile Load	Press. Load	σ_1	σ_2	Type Fail.
2	4-23-53	74.3	1.00	1.30	33150	37500	65170	55050	D
3	5- 1-53	-21.3	1.75	1.77	40980	30000	70920	40050	D?
4	5-13-53	7.3	∞	∞	47950	-	59362	-	D
A-1	5-28-53	-31.4	1.75	1.65	35000	28000	71480	43316	D
A-2	5-28-53	- 5.4	2.00	1.87	35700	24000	69444	37128	D
A-3	5-29-53	-33.4	1.00	1.08	16100	25500	48371	44931	D?
A-4	5-29-53	3.5	1.25	1.22	28000	36000	68098	55692	D?
A-5	6- 2-53	-47.5	1.00	1.06	24750	40000	65665	61880	B
A-6	6- 2-53	-53.3	1.25	1.23	29000	36000	68789	55692	B

D- Ductile B- Brittle

A visual inspection of the specimens after testing was made to ascertain whether brittle or ductile fracture existed. The specimens were not photomicrographed due to the lack of time and facility for this type of study, and also to preserve the specimens for another group that may desire to continue this work and need the specimens as they are.

Tests #2 and #4 are not discussed here inasmuch as they were a preliminary series. As can be seen from the photograph in Figure 15, specimen #3 showed very slight elongation and very little necking down, leading to the conclusion that it was on the verge of a brittle fracture. Inspection of the fractured edges however showed the 45 degrees sloped-edge characteristic of a ductile break. In this, as in other specimens of the A-series, there is the possibility that there may be a short region of ~~the~~ brittle

failure changing to and propagating through the greater part of the break in a ductile manner.

Tests A-1 and A-2 again, show the characteristics of ductile failure although in some cases there may have been a minute region of brittle failure. There was approximately 25% elongation in the test sections and the characteristic silky sheen indicating necking down in the vicinity of the breaks. It is believed that some bending was introduced in A-1, probably due to a bit of foreign matter on the disc of the universal in the lower platen of the testing machine.

Specimens A-3, A-4, and A-6, all have the visual characteristics of ductile failure. A-3 failed with a considerably larger report than any of the other tests and at low values of stress, leading to the belief that this may have been brittle at the start and then propagated as ductile. Specimen A-6 is believed to have originated as brittle although here again if a brittle area exists, confirmation of this belief could be obtained only by means of microscopic examination. This specimen has a considerable amount of essentially 45 degree~~s~~ Lueder's Lines, and is the only one with such lining.

Specimen A-5, as can be seen from the photographs, failed in both longitudinal and circumferential directions. The circumferential breaks are very definitely brittle failures as indicated by the grainy structure and the lack of local necking in the vicinity. Chevrons on both circumferential breaks point to the crack origin in the longitudinal break section. Parts of the longitudinal break propagated as brittle and it is believed the origin of the fracture was in the ductile region. It is assumed

that failure started in the region of maximum bulging of the tube, or the ductile region. Here again, a microscopic examination of this area might reveal a brittle region of the origin changing to ductile and back again to brittle for the remainder of the break.

DISCUSSION OF RESULTS & CONCLUSIONS

It is felt that some work has been left undone in this effort. Namely, a thorough identification of the failures so that it could be stated more positively where brittle and where ductile failure occurred.

On the other hand, this thesis was more directed to overcoming difficulties in the setting-up and to methods of procedure rather than testing and interpreting a large numberof tubes. It is felt that therein we attained our ends. Refinements in the refrigeration system are certainly desireable. We feel that tests on A-5 and A-6 were nearly into the temperature range where brittle failure would definitely have occurred. A higher capacity and more positively controlled pumping arrangement is also desireable; but both refrigeration and pumping were relatively minor problems to us compared to the end attachment and end removal problem.

RECOMMENDATIONS

Since the investigation to this point has yielded no definite results, these recommendations are centered about procedural methods and are not based on any conclusions which we reached. In general, this investigation must be carried to further extremes. Instead of testing only six specimens, literally hundreds of specimens should be tested over the course of several years. This series of test should not be conducted in a haphazrd manner, but rather should have a definite pattern laid out. Since there are two variables involved, temperature and stress ratio, one should be held constant while the other one is varied. Take a stress ratio of 1.75, hold it, and with six specimens, vary the temperature in the following manner: -60 degrees F, -40 degrees F, -20 degrees F, 0 degrees F, 20 degrees F, 40 degrees F. By noting the type of failure and the ultimate value of stress, a definite pattern will result. It is important that a complete scanning or bracketing method be used so that there are no blind spots left. The authors feel ~~that~~ by using this method that the pattern will definitely show that the stress ratio involved has a definite effect on whether or not a brittle fracture results and on the transition temperature. If this can be proven, a whole new field of investigation is opened up and we might be a little closer to the ultimate answer.

The above recommendations are general, but there are some

specific hints, some that were learned by experience, some that were the results of considerable hindsight that we would like to pass along. We list them here for the person or persons that may desire to continue this experiment:

1. Considerable thought was given to the possibility of notching the specimen. It was generally felt that if a suitable notch could be decided upon and if the notch could be accurately reproduced so that all the specimens would have exactly the same size notch in the same location then, by all means, notch the specimens. The problem was to be able to measure the internal diameter of the notch so that a reasonably accurate cross sectional area could be determined. It might be well to look into this aspect.

2. The use of the SR-4 type resistance strain gauge did not prove feasible. It was tried , and the results used to check on the stress ratio in the elastic range, but for the very reason that we were interested in the condition beyond the elastic range ~~proved~~ where the gauges broke loose and were no longer of value to us, proved that the use of this type of strain gauge was unsatisfactory. We recommend that this type of strain gauge not be used in the future. However, this does not close the door on strain evaluation, for there are several other types of strain gauges that can stand investigation. One is the use of the inductance type of strain gauge on which great strides have recently been made. No adhesion of the gauge to the specimen is neccessary ; simple labratory equipment can be used; the gauges can be used over again, and

temperature compensation can be accomplished with out difficulty. The only difficulty will be the method of attachment for biaxial analysis.

Another method of strain analysis which can be tried is the use of a grid that has been photographically superimposed on the test specimen. This method has been tried and used successfully on explosion fractured plates. The neccessary information on the subject is available at the Metallurgy Branch of the Material Laboratory, New York Naval Shipyard, Brooklyn, New York.

3. If time and material are available, several sets of collar assemblies should be manufactured from the detailed drawings accompanying this thesis to facilitate rapid testing. The ideal set-up would be to have the six specimens that are to be run as a series all assembled and ready for testing so that with one charge of dry ice in the system the series could be run together. This would also facilitate the precooling of the specimens which is also to be desired to reduce the waiting time while the system is reaching equilibrium. A ready supply of wedges should be kept on hand in the event that any are damaged and need replacement.

4. Refinement of the oil system to obtain greater flexibility would also be desireable. As the system now stands, pressures up to 4000 pounds per square inch are obtainable without too much difficulty, but maintaining this pressure while the specimen is elongating or expanding becomes quite a problem from a physical standpoint. The use of an electrically driven pump

of the gear type with a pressure relief by-pass so that any pressure could be maintained with little effort, if any, on the part of the operator appears to be the answer.

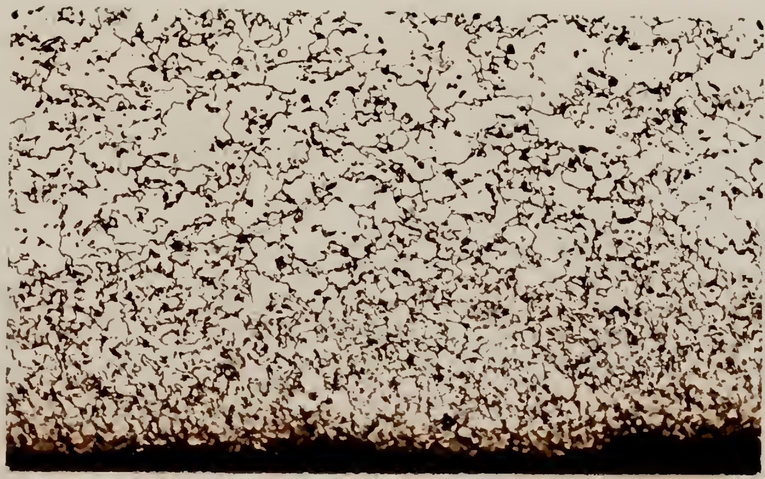
5. In the matter of cooling, we were able to get down to -54 degrees Fahrenheit, which under most conditions should be satisfactory. In the event that lower temperatures are required, they can be obtained by loading only the specimen box with chipped dry ice, disconnecting the the refrigerator, and running the blower at full speed. With precooling, and further insulation of the specimen box, this method of cooling should give temperatures somewhat below - 70 degrees Fahrenheit.

INDEX TO FIGURES

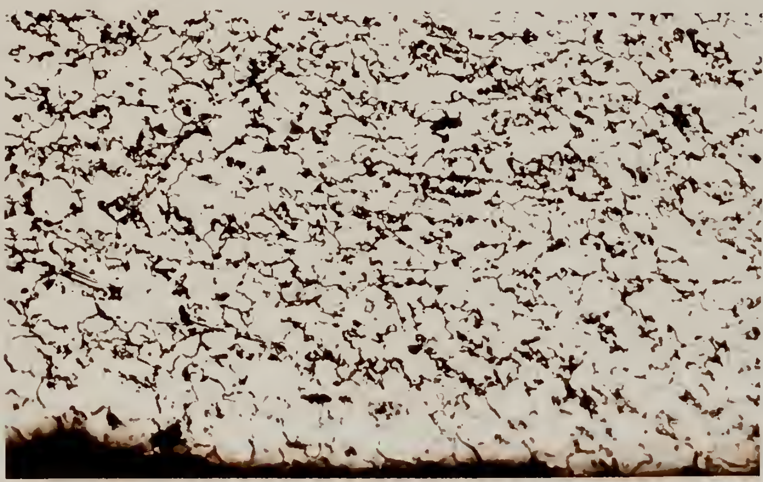
16. Series "A" Test,1-4,Photograph.

17. Series "A" Test,5&6,Photograph.

18. Series "A" Tests, Arranged in order of stress ratio, Photograph.



Transverse Section Prior
to Test



Longitudinal Section Prior
to Test

Magnification 100X
Etch: 2% Nital and 5% Picral

Figure 1. TYPICAL MICROSTRUCTURES OF MILD STEEL SEAMLESS TUBING PRIOR TO TESTING.

U.S.Naval Postgraduate School
Webb Institute of Naval Arch.

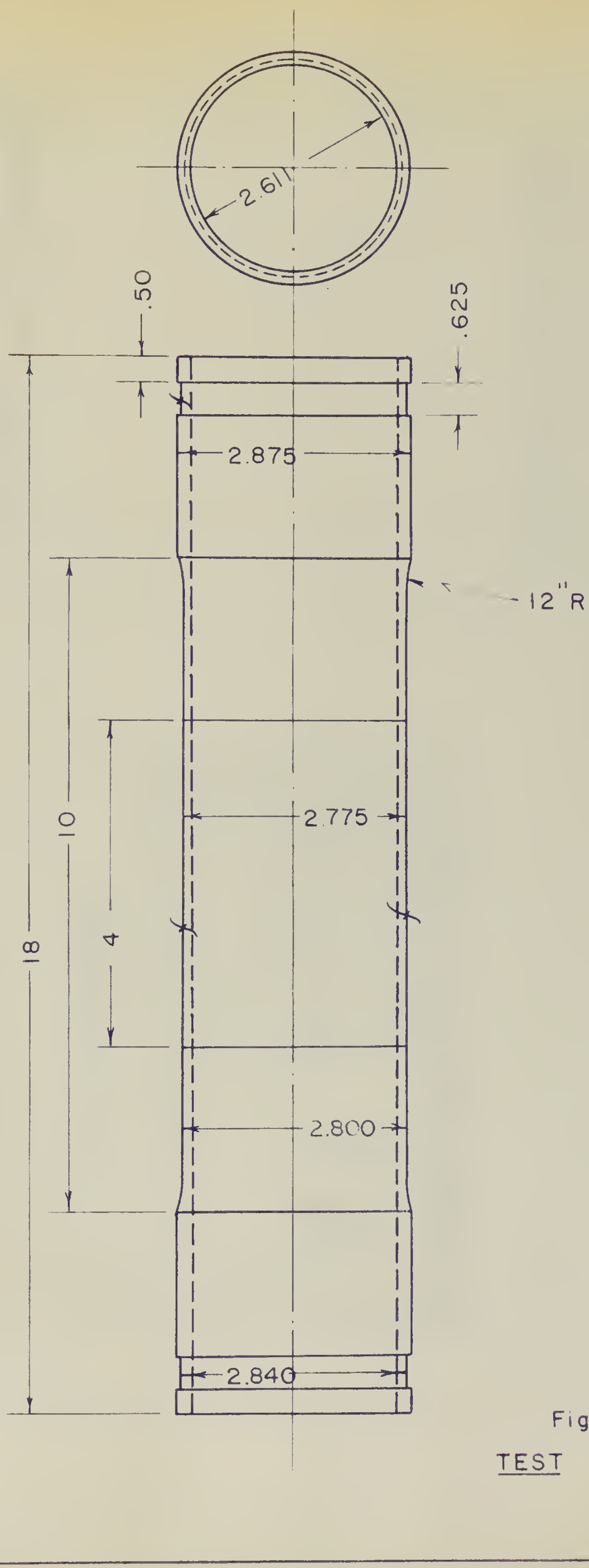


Figure 2

TEST SPECIMEN

Not to scale

Figure 3
TEST SPECIMEN AS MACHINED

Figure 4
TEST SPECIMEN WITH GAGES

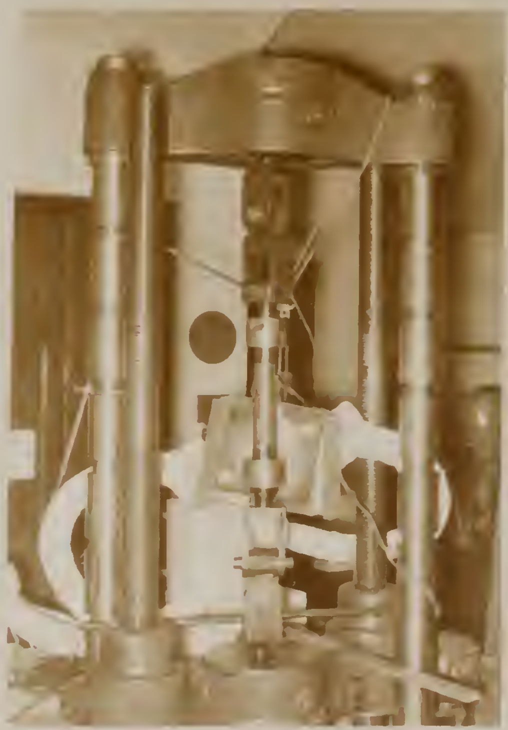
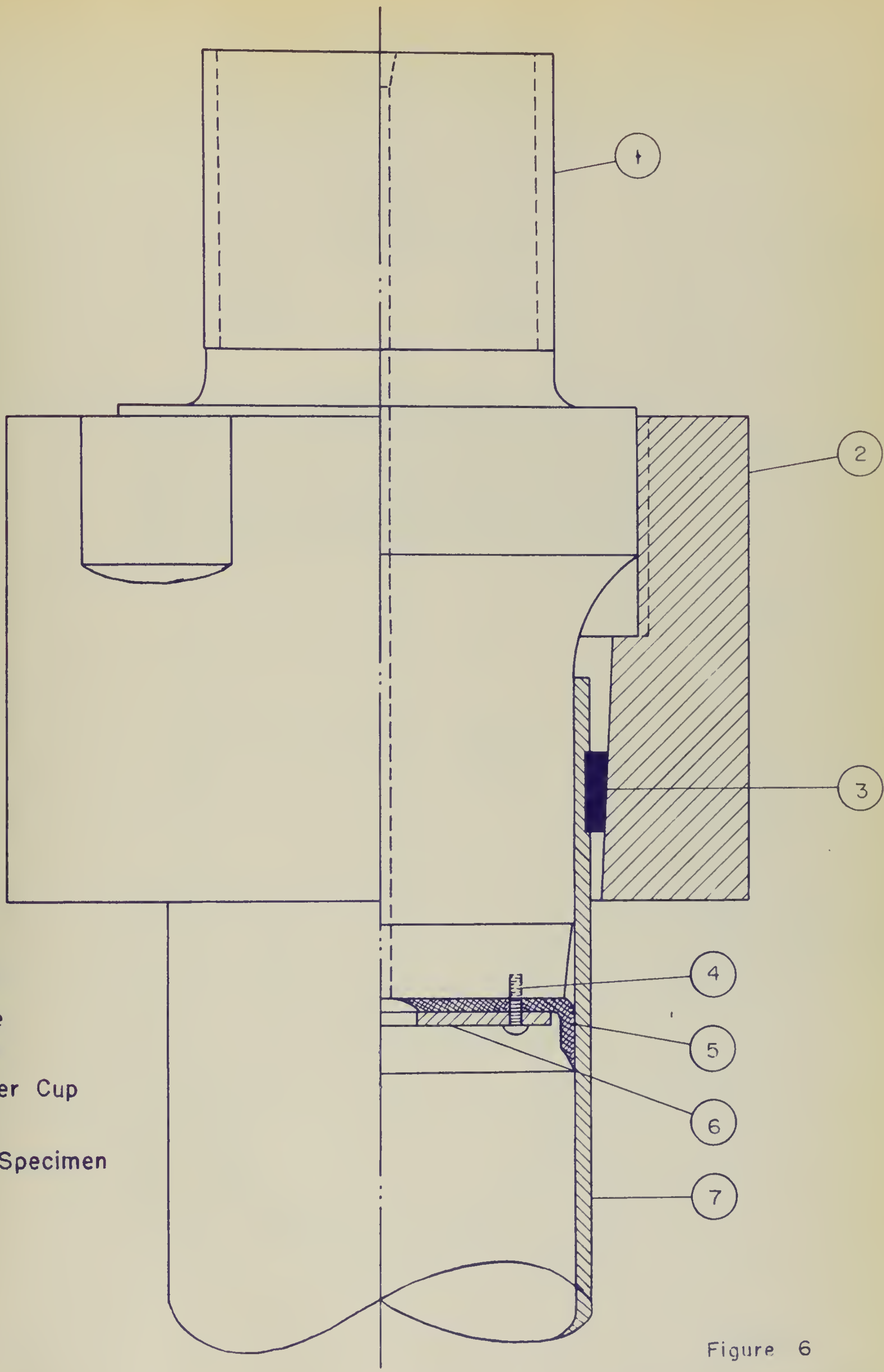


Figure 5
SPECIMEN SET-UP FOR TESTING

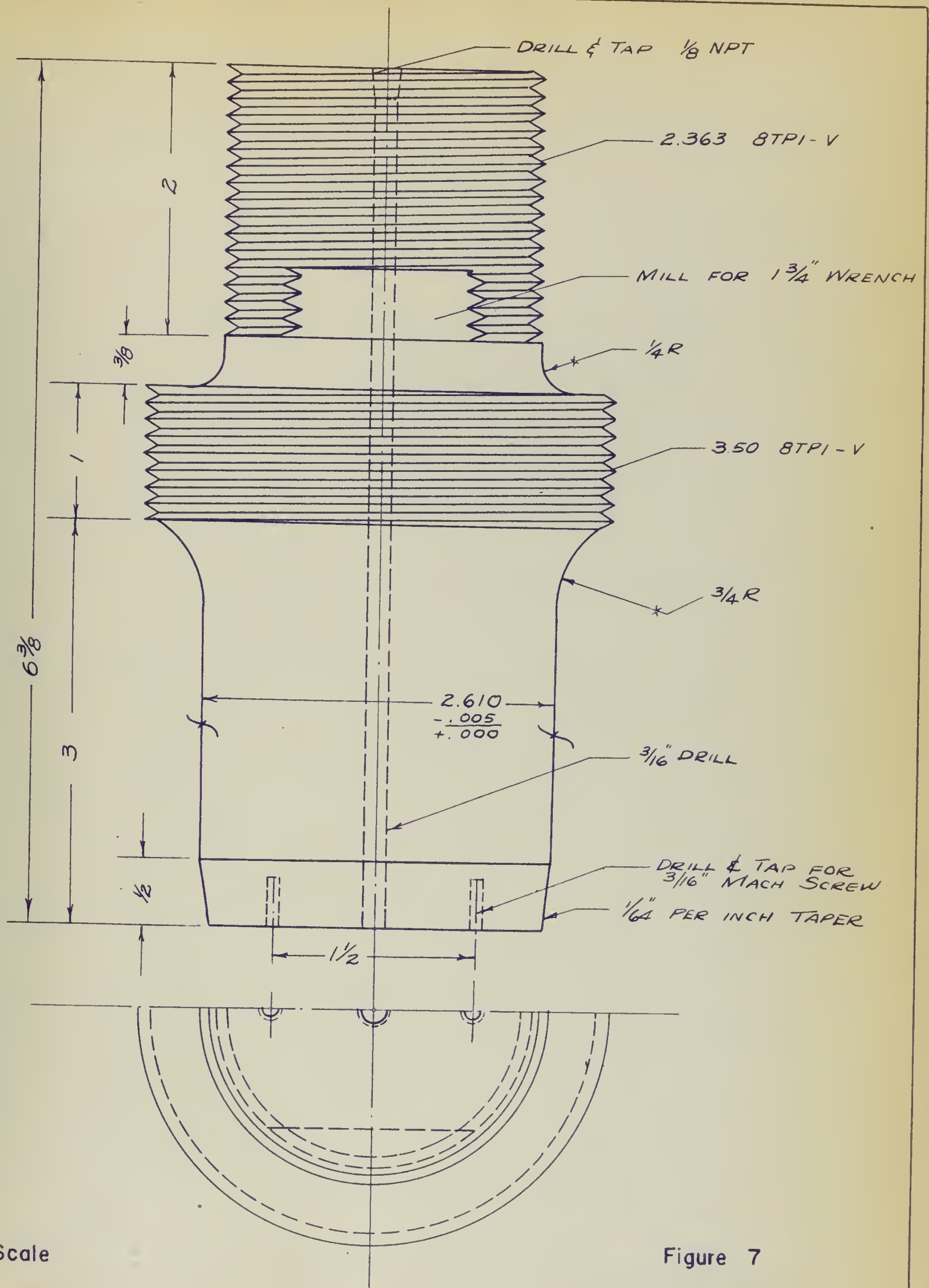


1. Plug
2. Collar
3. Wedge
4. Screw
5. Leather Cup
6. Ring
7. Test Specimen

Figure 6

COLLAR ASSEMBLY

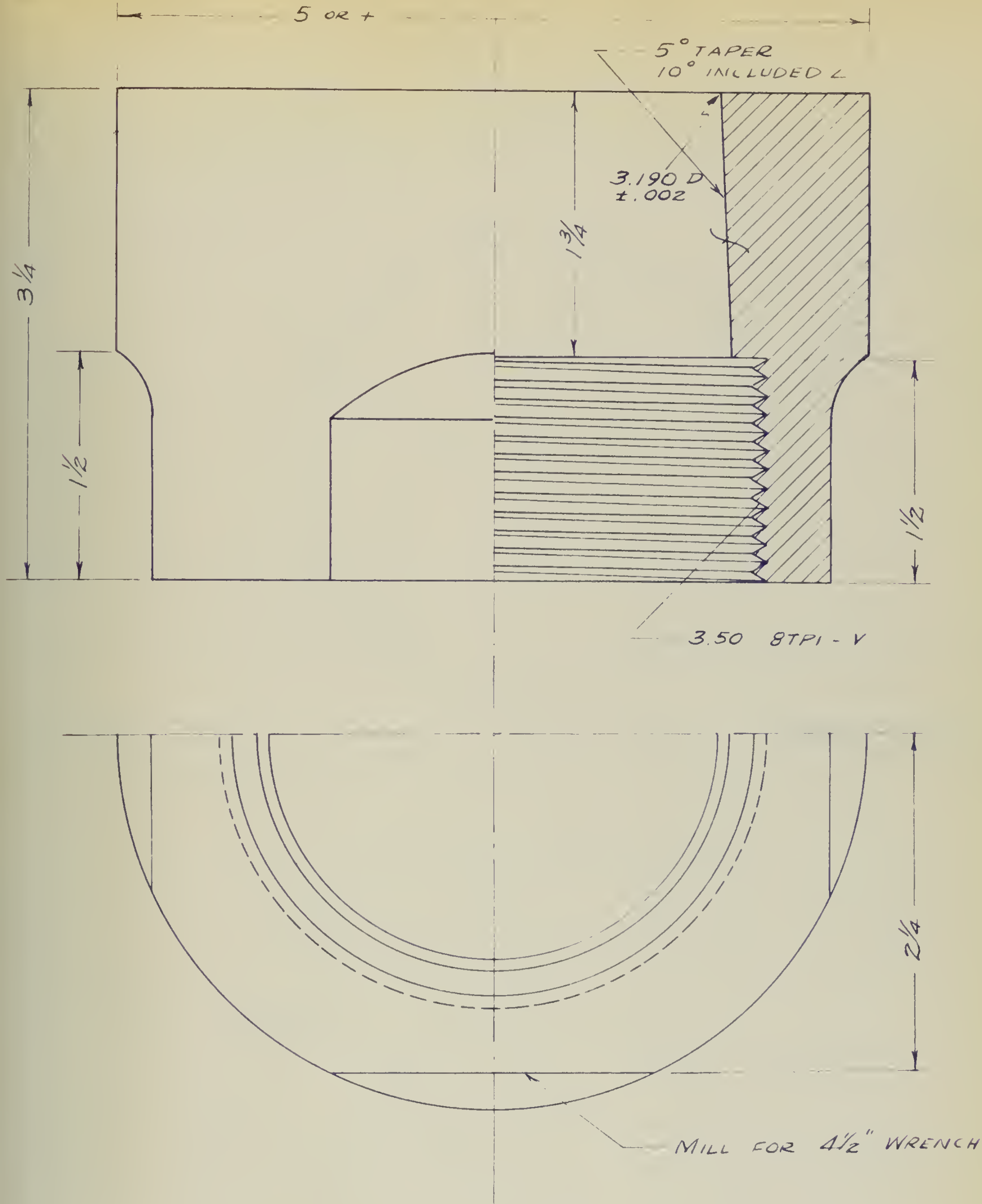
Full Scale



Full Scale

Figure 7

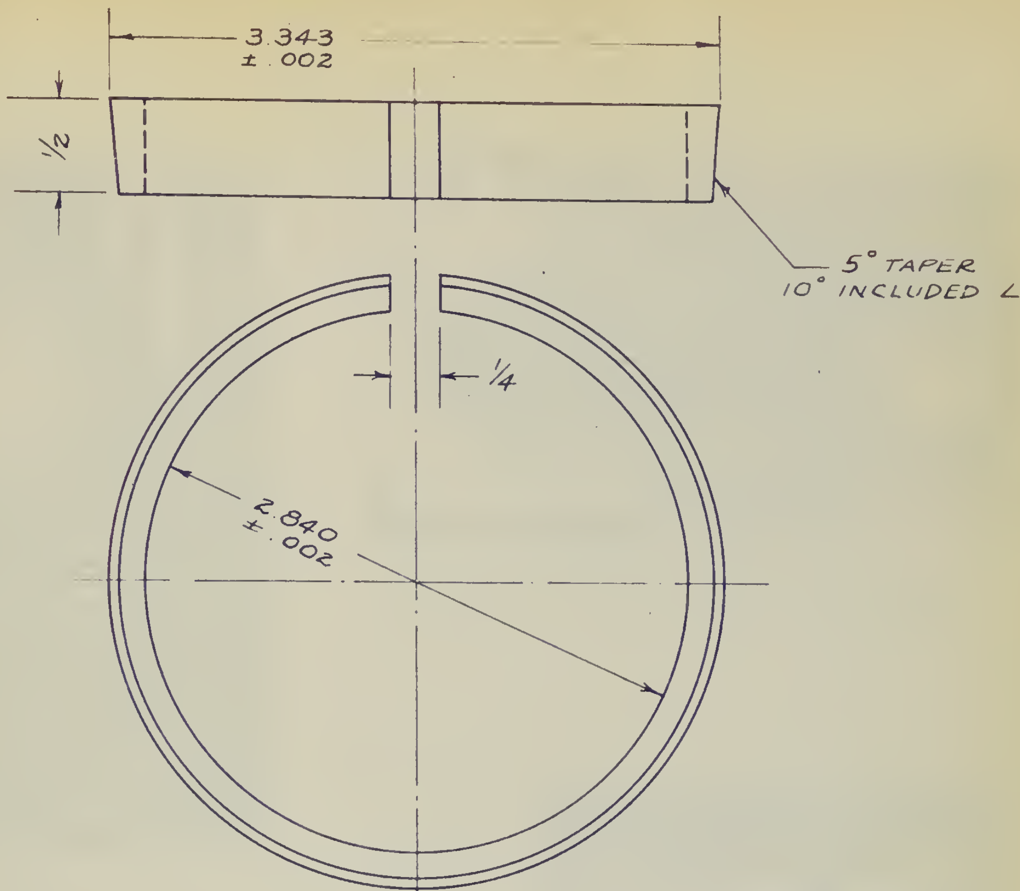
PLUG DETAIL



Full Scale

Figure 8

COLLAR DETAIL



Full Scale

WEDGE DETAIL

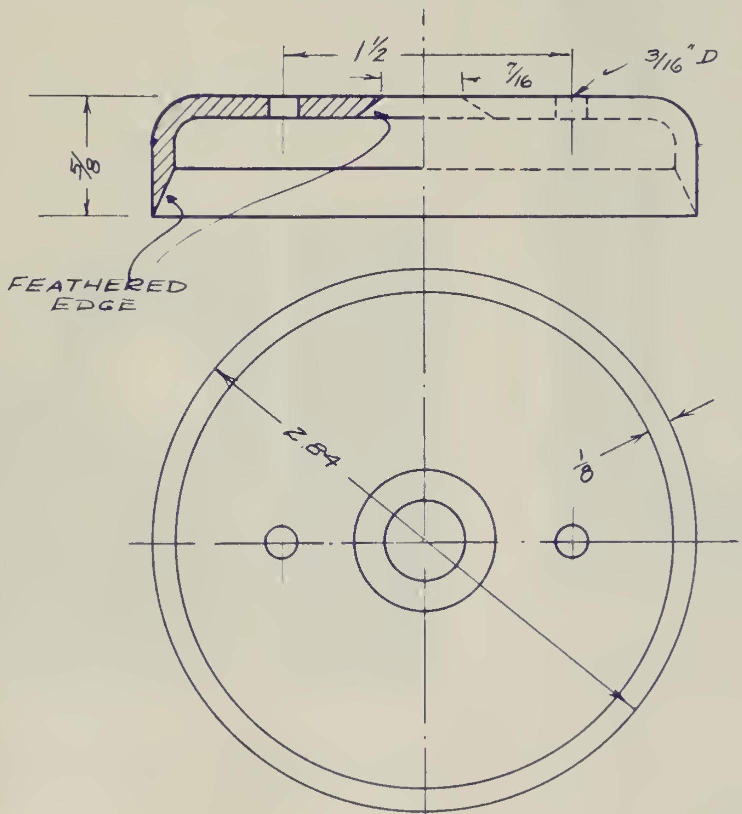


Figure 9

Full Scale

LEATHER SEAL DETAIL

Figure 10
200,000 LB TENSILE MACHINE
CONTROL STATION

Figure 11
AIRCO "DB" PRESS USED FOR OIL PRESSURE

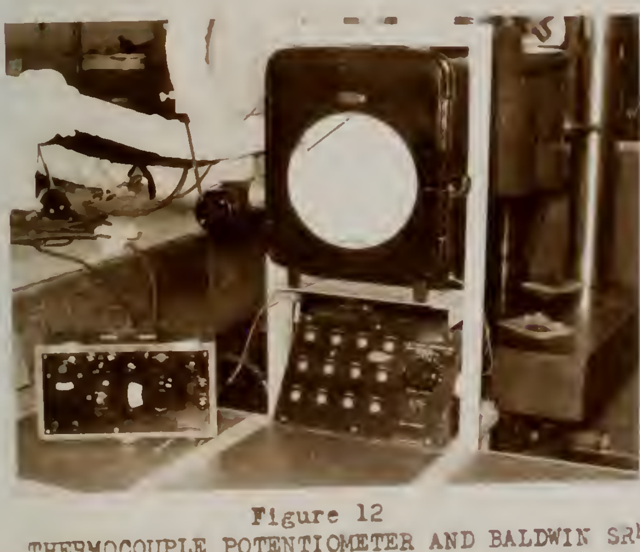


Figure 12
THERMOCOUPLE POTENTIOMETER AND BALDWIN SR4
STRAIN GAGE BALANCING AND RECORDING UNIT

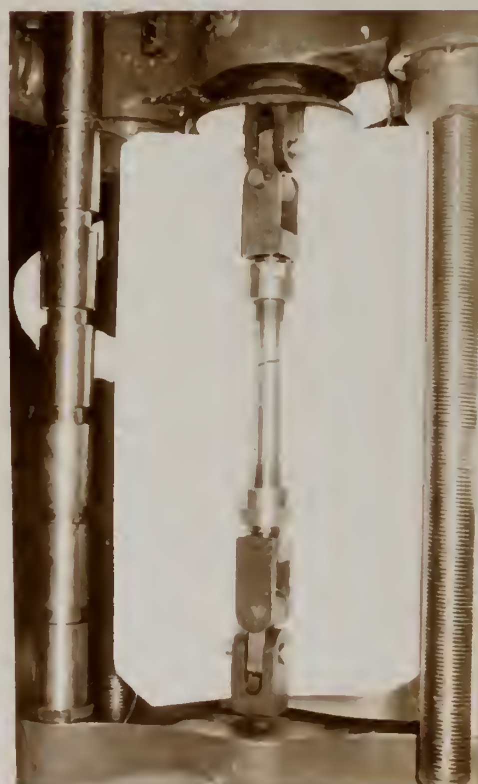


Figure 13
TENSILE MACHINE SHOWING METHOD
OF UNIVERSAL ATTACHMENT

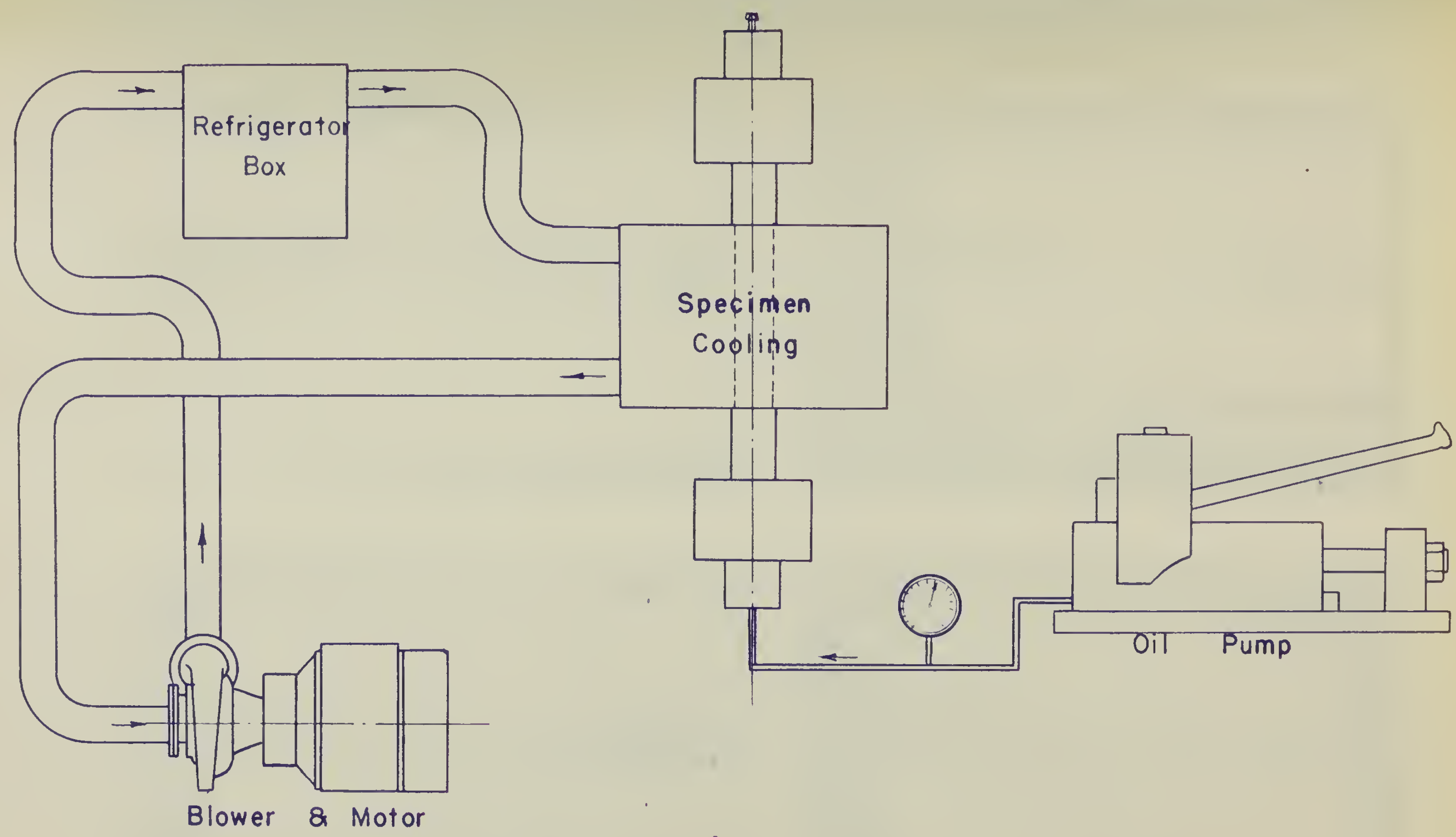
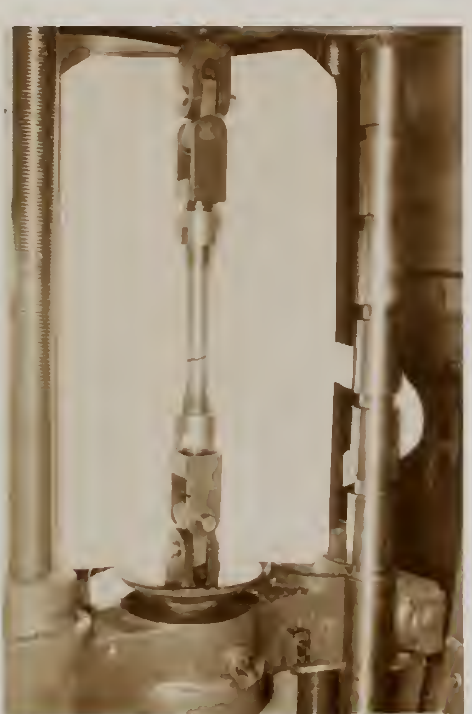
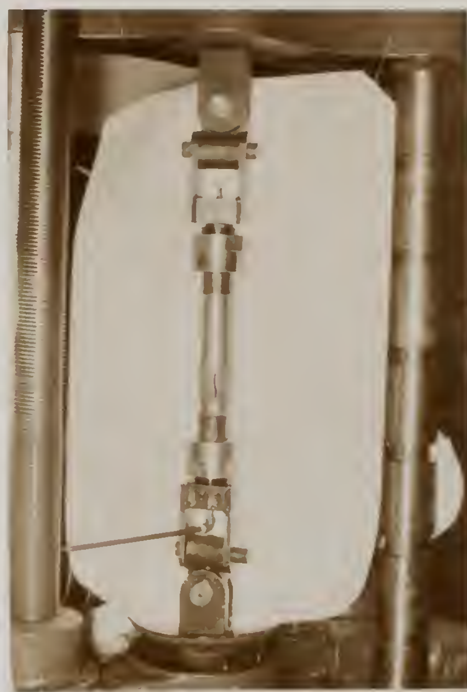


Figure 14

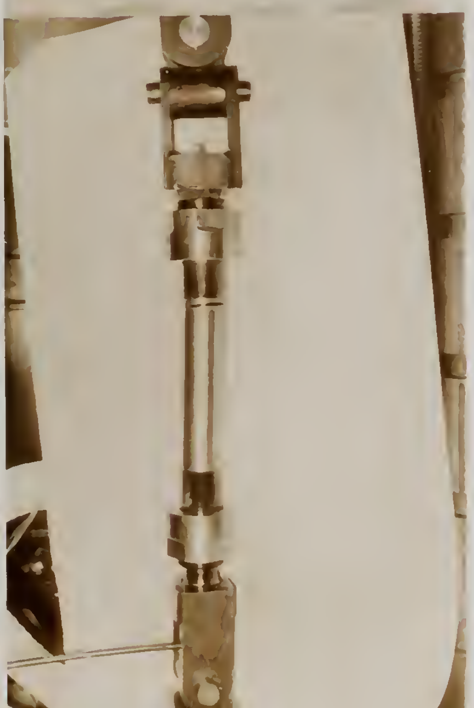
SCHEMATIC OF OIL & COOLING SYSTEMS



TEST NO. 1



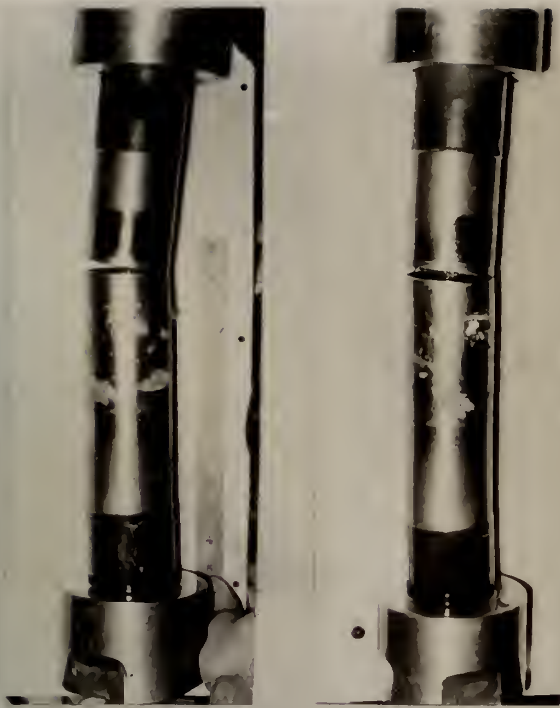
TEST NO. 2



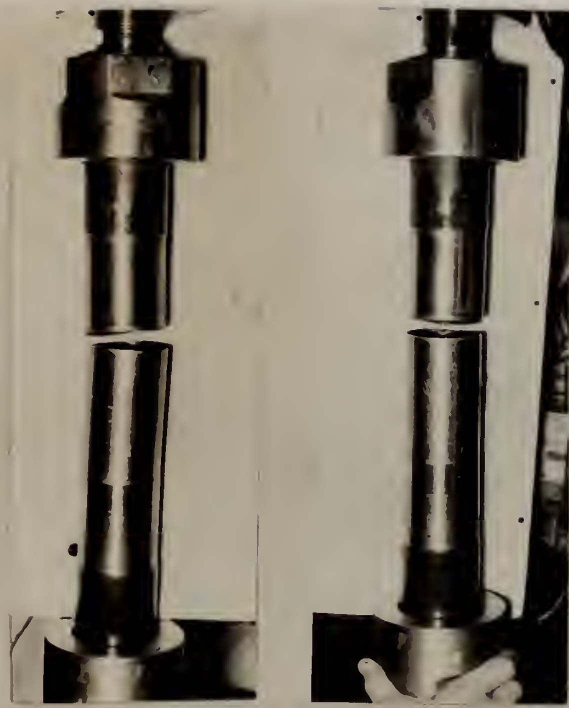
TEST NO. 3

TEST NO. 4

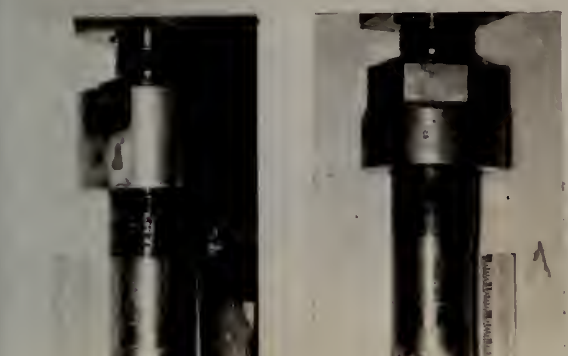
FIGURE 15



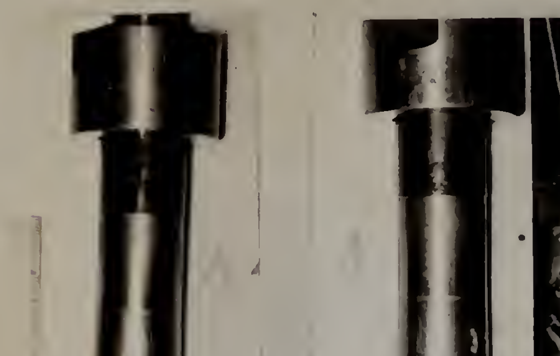
TEST A-1
Stress Ratio 1.75
Failure Temperature -31 F



TEST A-2
Stress Ratio 2.00
Failure Temperature -6 F

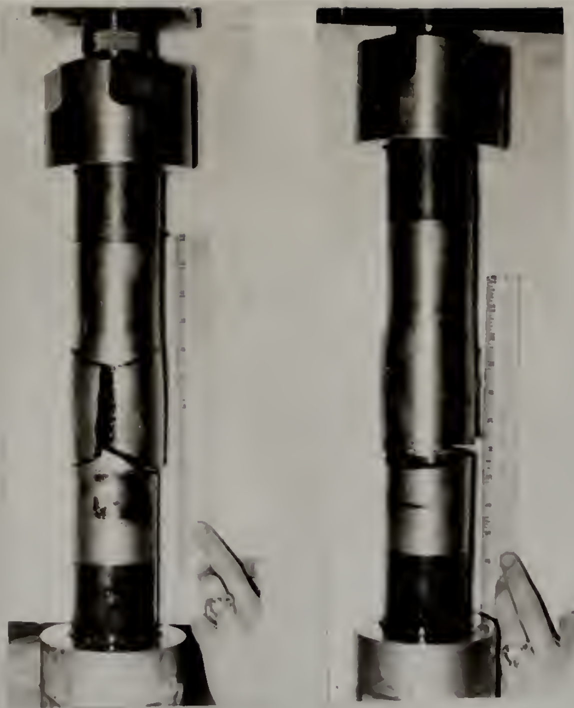


TEST A-3
Stress Ratio 1.00
Failure Temperature -34 F

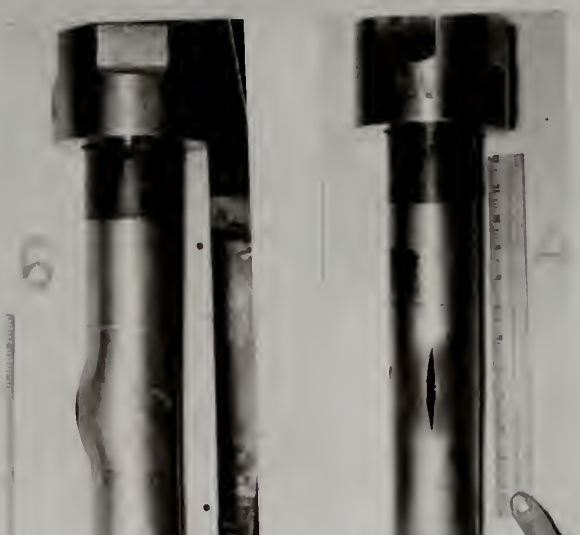


TEST A-4
Stress Ratio 1.25
Failure Temperature 3.5 F

FIGURE 16



TEST A-5
Stress Ratio 1.00
Failure Temperature -48 F



TEST A-6
Stress Ratio 1.25
Failure Temperature -54 F

FIGURE 17

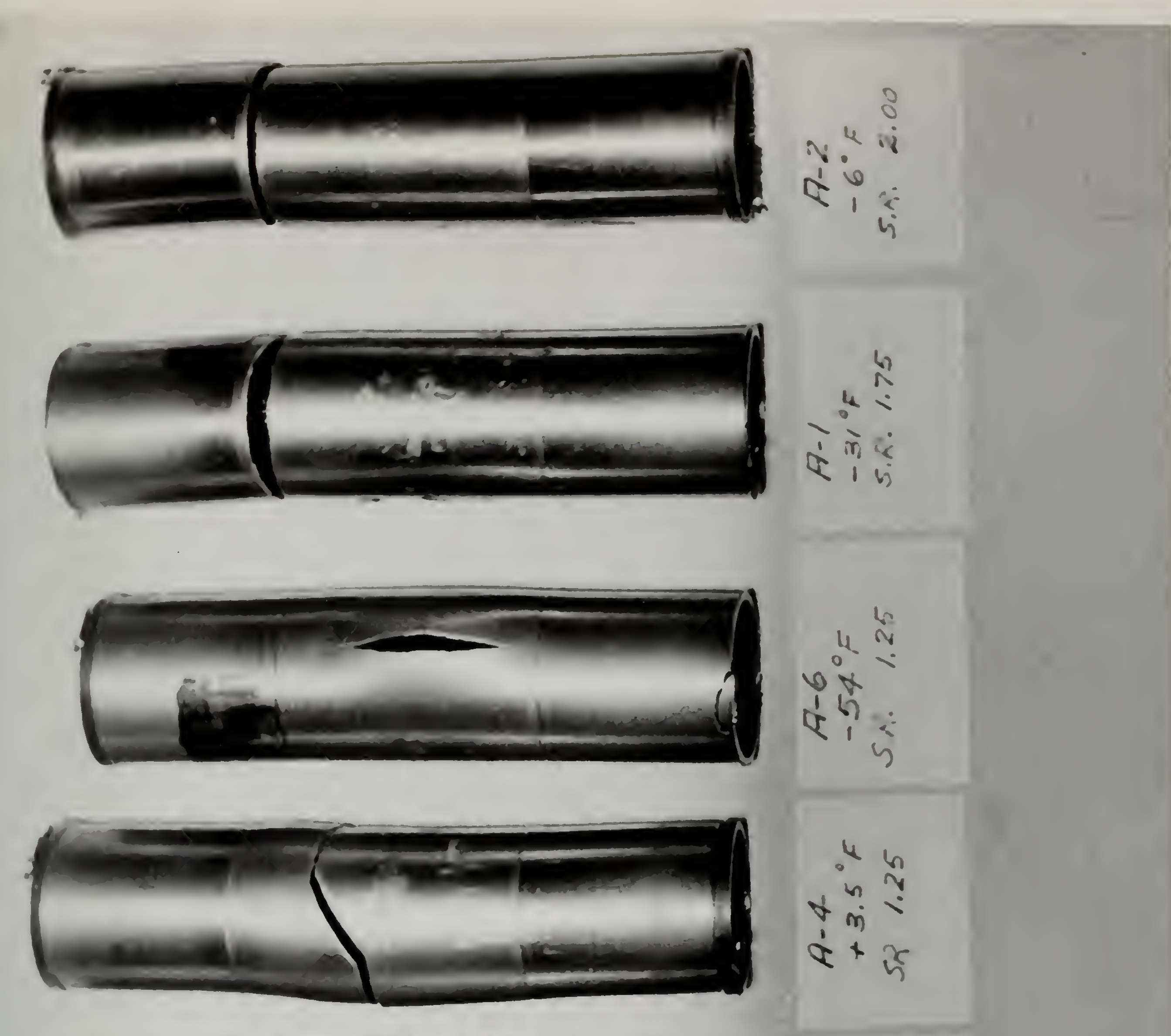

A-3
-34°F
S.R 1.00
A-5
-45°F
S.R. 1.00
A-4
+3.5°F
SR 1.25
A-6
-54°F
S.R. 1.25
A-1
-31°F
S.R. 1.75
A-2
-6°F
S.R. 2.00

FIGURE 18

APPENDIX

Properties of the Steel:

1.Chemical Composition:

Carbon .19%

Manganese.54%

Silicone .21%

Nickle .09%

Aluminum .013%

Copper .06%

Chrome .06%

Moly .013%

2.Physical Properties:

Yield Point: 34,750 psi

Ultimate Strength: 61910 psi

Elongation in 2 ": 35 %

Reduction in Area: 31.4%

Hardness, RockwellB:68-72

3.Manganese to carbon ratio: 2.84

4.Etching:

40 seconds Nital 2%,30 seconds Picral5 %

5.History of pipe as received from the mill:

a) not annealed, probably normalized

b) low carbon

c) evidence of cold working at the edges.

TEST DATA

Formulas Used:

$$\sigma_1 = \frac{p\, d_p^2 + 4L/\pi}{4t_p(d_p + t_p)}$$

$$\sigma_2 = \frac{p\, d_p}{2\, t_p}$$

For preliminary test # 2,3,&4:

$d_p = 2.611''$

$t_p = .095''$

$p - P/10.29$

$\sigma_2 = 1.335\ P$

$\sigma_1 = .644P + 1.238L$

For Test # A1,A2,A4,A5,&A6:

$d_p = 2.611''$

$t_p = .082''$

$p = P/10.29$

$\sigma_2 = 1.547P$

$\sigma_1 = .750\ P + 1.441\ L$

For Test # A3:

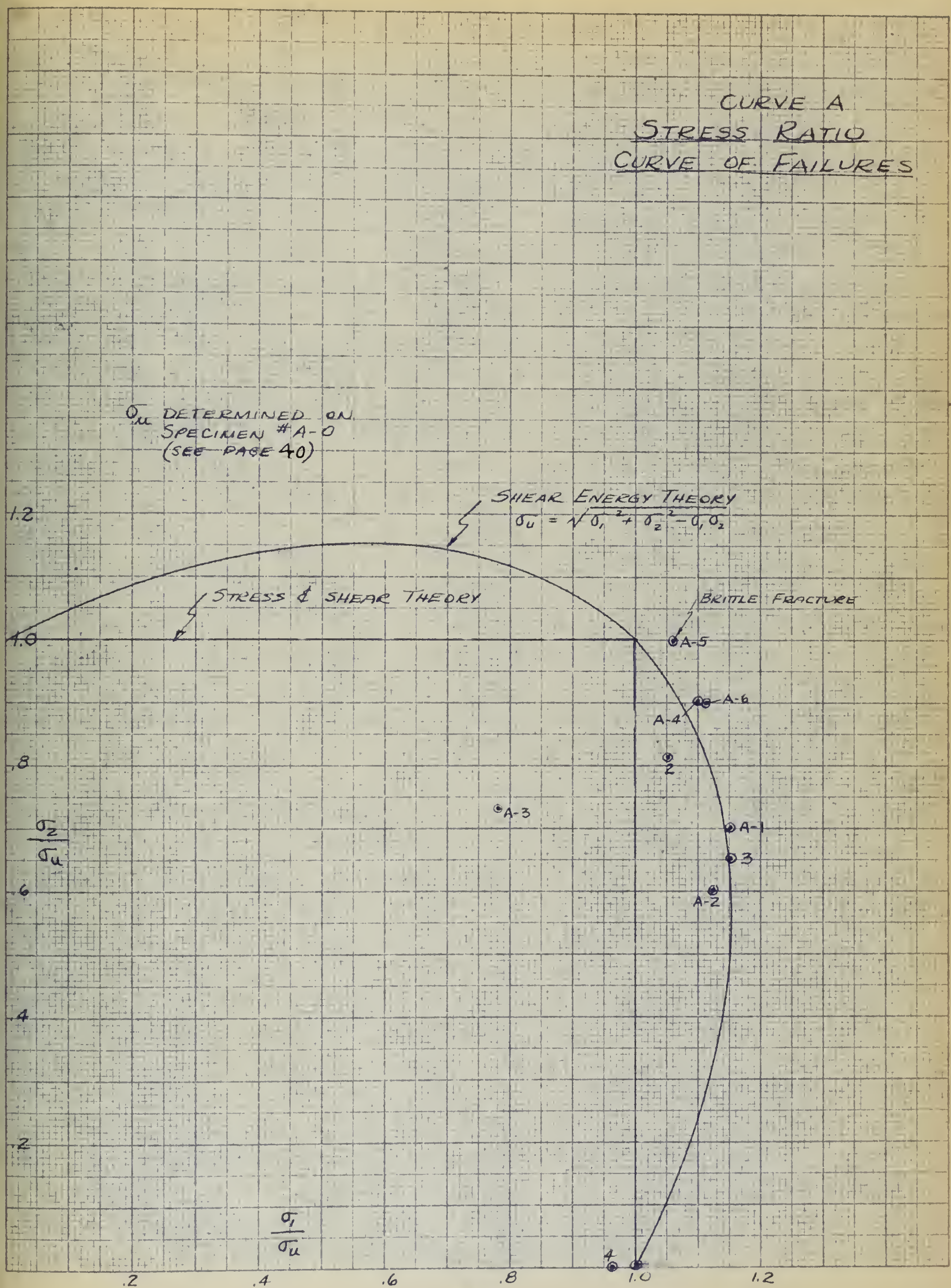
$d_p = 2.611''$

$t_p = .072''$

$p = P/10.29$

$\sigma_2 = 1.762\ P$

$\sigma_1 = .8574P + 1.647L$



CURVE A
STRESS RATIO
CURVE OF FAILURES
σ_u DETERMINED ON SPECIMEN #A-0
(SEE PAGE 40)
SHEAR ENERGY THEORY
$\sigma_u = \sqrt{\sigma_1^2 + \sigma_2^2 - \sigma_1\sigma_2}$
STRESS & SHEAR THEORY
BRITTLE FRACTURE
A-5
A-6
A-4
2
A-3
A-1
3
A-2
4
$\frac{\sigma_2}{\sigma_u}$
$\frac{\sigma_1}{\sigma_u}$
1.2
1.0
.8
.6
.4
.2

Final determination of the value of the modulus of elasticity from the experimental values tabulated in the graphs:

1. The value of "E" = 40 x 10^6 tangent θ

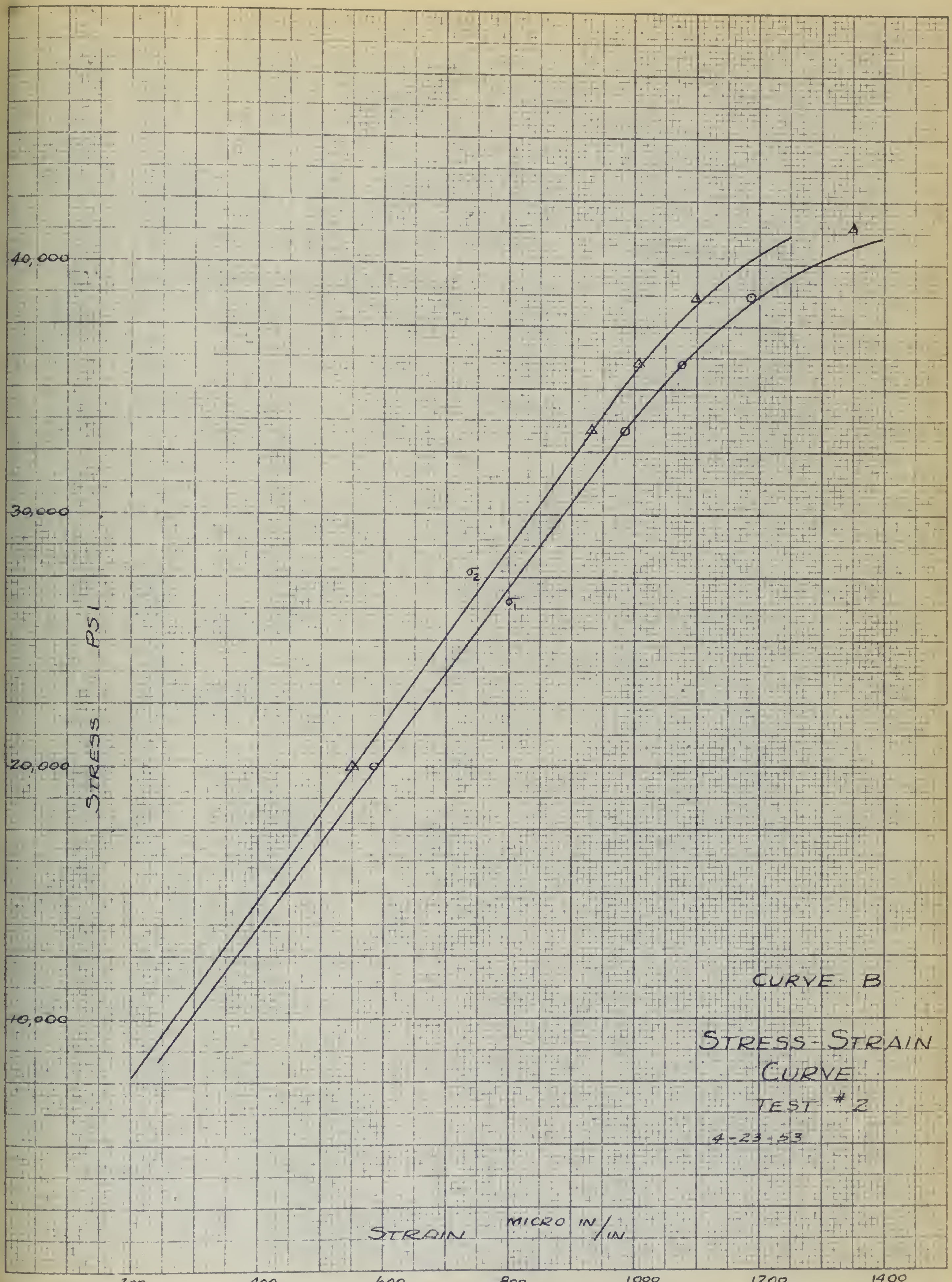
Test	θ_1	θ_2	E_1	E_2
P2	53.2	54.3	29.9	28.7
P3	56.6	71.8	26.4	13.2
P4	51.3	-	32.0	-
A1	51.9	65.1	31.4	18;6
A2	53.0	68.7	30.1	15.6
A3	55.8	55.0	27.2	28.0
A4	57.0	63.0	26.0	20.4
A5	58.3	58.3	24.7	24.7
Average value-			28.5	21.3

Test Data for Preliminary Test No.2:

σ_1	σ_2	Gage Reading	Elongation ϵ_1	Gage Reading	ϵ_2 Elongation
0	0	4980	0	2700	
20022	20025	5560	580	3250	550
33370	33375	5965	985	3630	930
36040	36045	6055	1075	3705	1005
38709	38715	6165	1185	3800	1100
41379	41385	6505	1525	4050	1350
44049	44055	3160	8180	9250	6550
46718	46725	off scale		off scale	
49388	49395				
65170	50050	pipe "busted" at this point			

Stress ratio was 1, Temperature 74.3 degrees F.

Date 4-23-53

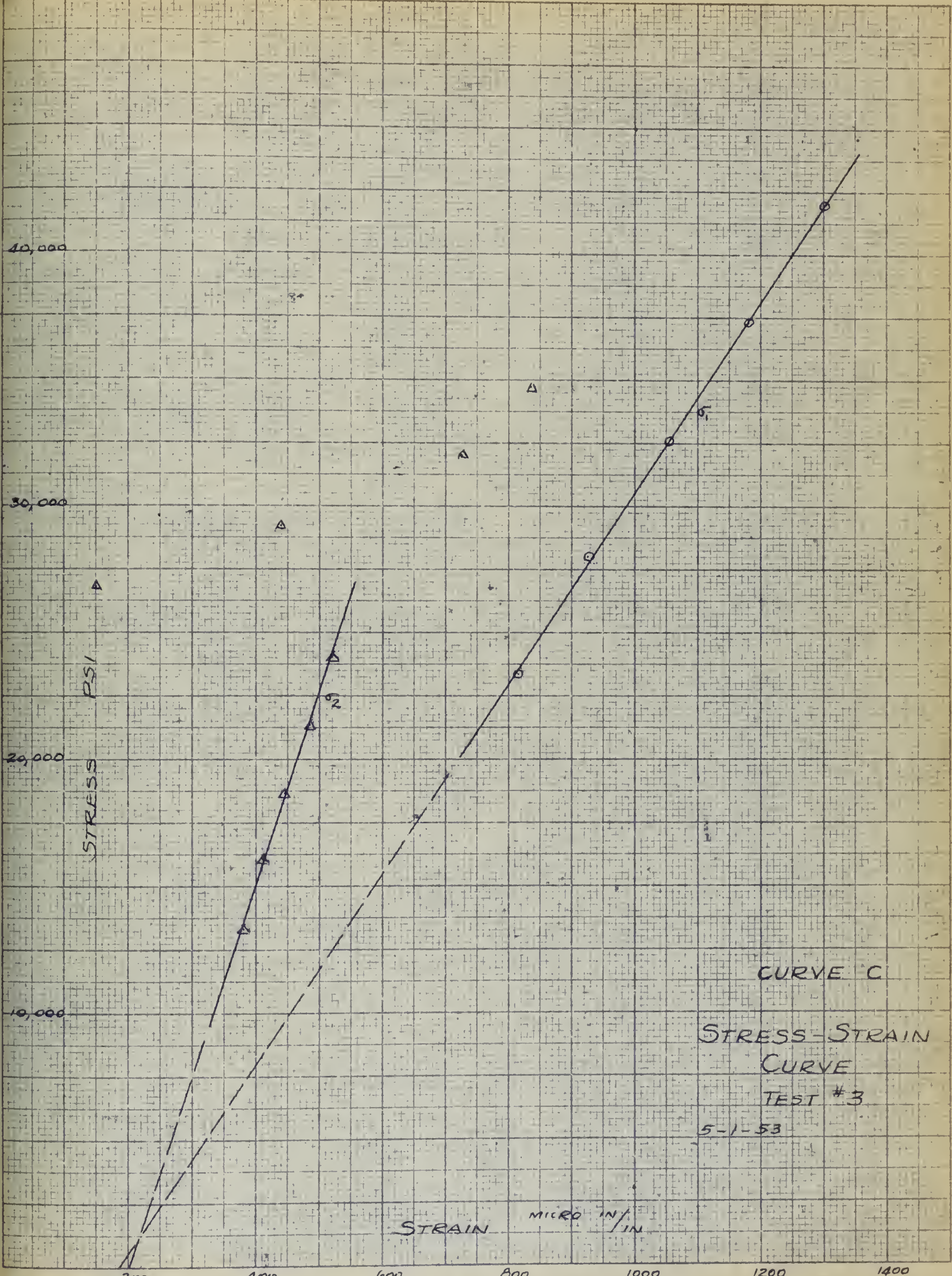


40,000
30,000
20,000
10,000
STRESS PSI
σ_2
σ_1
CURVE B
STRESS-STRAIN
CURVE
TEST # 2
4-23-53
STRAIN MICRO IN/IN
200
400
600
800
1000
1200
1400

Test Data for Preliminary Test No.3:

σ_1	σ_2	Gage Reading	Elongation ϵ_1	Gage Reading	Elongation ϵ_2
6	0	4335	0	5215	0
23351	13350	5150	815	5595	380
28019	16020	5260	925	5625	410
32662	18690	5390	1055	5660	445
37317	21360	5515	1180	5700	485
42022	24030	5635	1300	5735	520
46702	26700	off scale	5365	5365	off scale
51370	29370				
56062	32040				
60693	34710				
65324	37380				
70053	40050				
70920	40050	pipe "busted" at this point.			

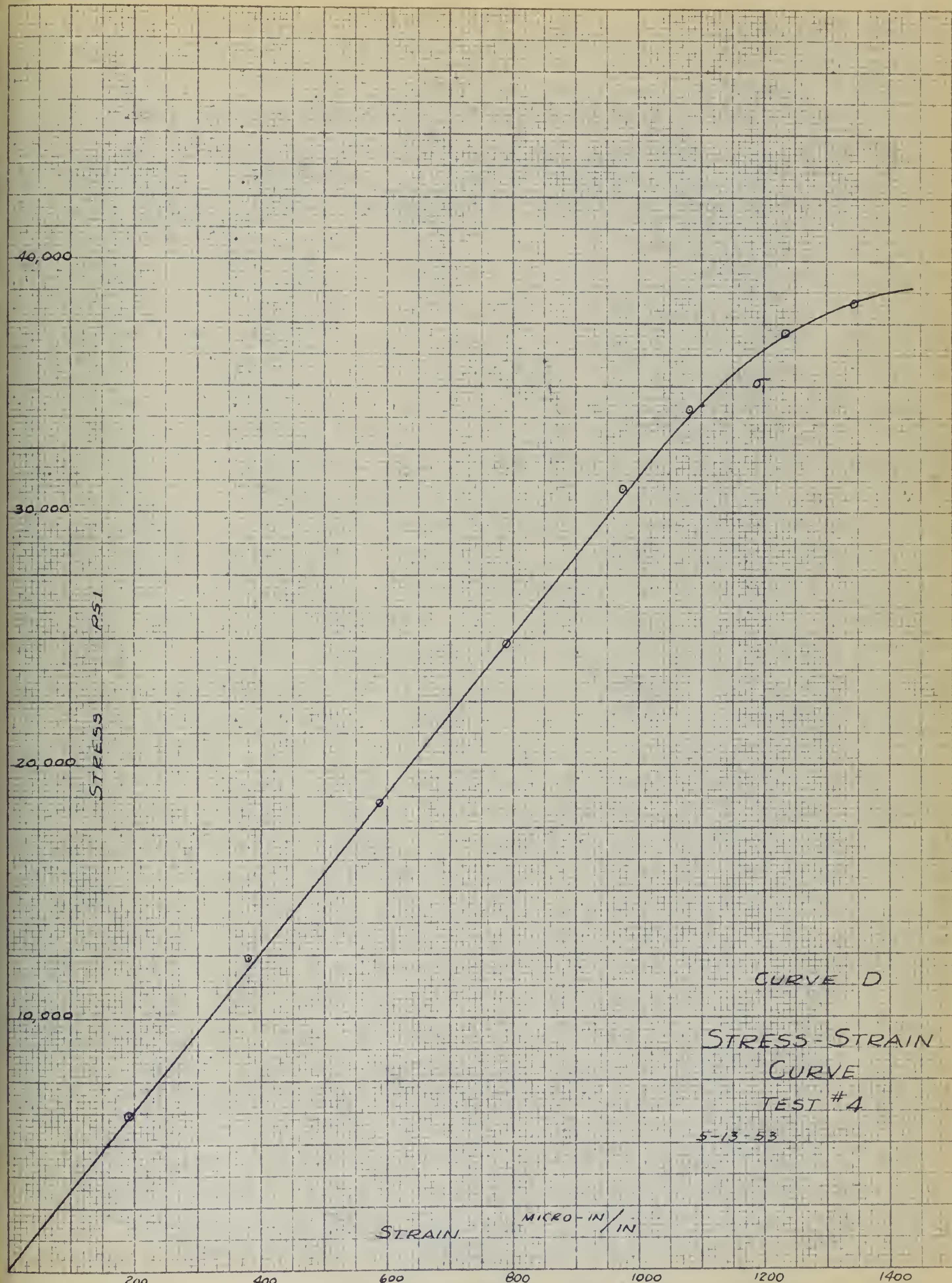
Date 5-1-53, Temperature: -25.9 degrees F, Stress Ratio: 1.77


40,000
30,000
20,000
10,000
STRESS PSI
σ_1
σ_2
STRAIN MICRO IN/IN
200
400
600
800
1000
1200
1400
CURVE C
STRESS-STRAIN
CURVE
TEST #3
5-1-53

Test Data for Preliminary Test # 4:

σ_1	σ_2	Gage Reading	Elongation ϵ_1	Gage Reading	Elongation ϵ_2
0	0	4535	0	5805	0
6190	0	4725	190	5745	-60
12380	0	4915	380	5675	-130
18570	0	5120	585	5620	-185
24760	0	5325	790	5555	-250
30950	0	5510	975	5505	-300
34045	0	5615	1080	5460	-345
37140	0	5770	1235	5425	-380
38378	0	5880	1345	5410	-395
39616	0	offscale		5350	-455
59362	0	pipe busted at this point			

Date-5-13-53 , Temperature-6 degreesF: Stress Ratio-Infinity


40,000
30,000
20,000
10,000
STRESS PSI
σ
CURVE D
STRESS-STRAIN
CURVE
TEST #4
5-13-53
STRAIN
MICRO-IN/IN
200
400
600
800
1000
1200
1400

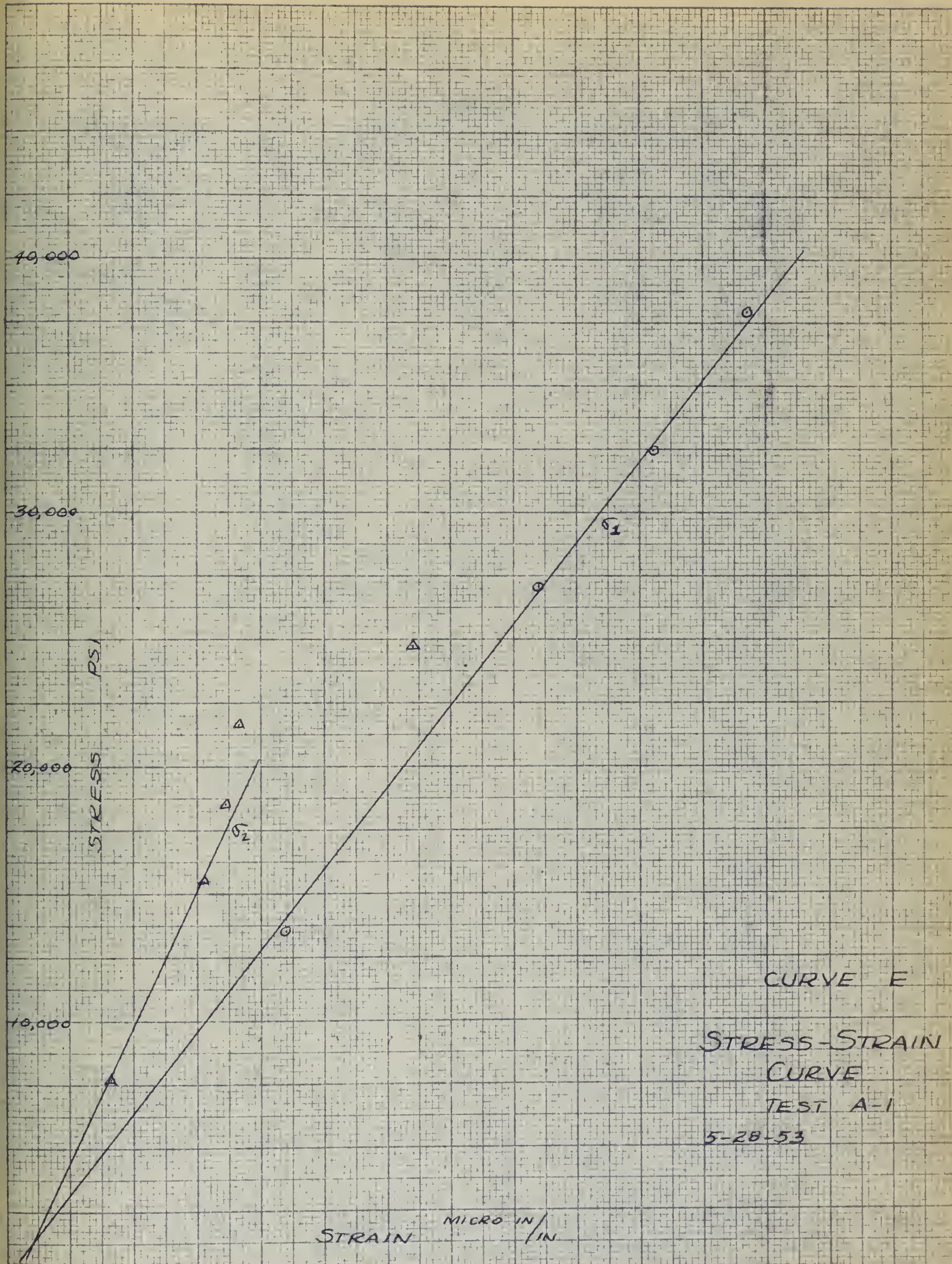
Data for Test A-O:

This pipe was broken at room temperature of 74 degrees F. The specimen broke at a tensile load of 42950 pounds. This give $\sigma_1 = 1.441\ L = 1.441 \times 42950 = 61890$ pounds per square inch.

Data for Test No.A-1:

σ_1	σ_2	Gage Reading	Elongation ϵ_1	Gage Reading	Elongation ϵ_2
0	0	6185	0	6490	0
13536	7735	6625	440	6655	165
27073	15470	7025	840	6800	310
32487	18564	7205	1020	6835	345
37902	21658	7355	1170	6855	365
43316	24752	off scale		7130	640
48731	27846				
54145	27846				
54145	30940				
59560	34034				
64974	37128				
71480	40222				
71480	43316	specimen broke at this point			

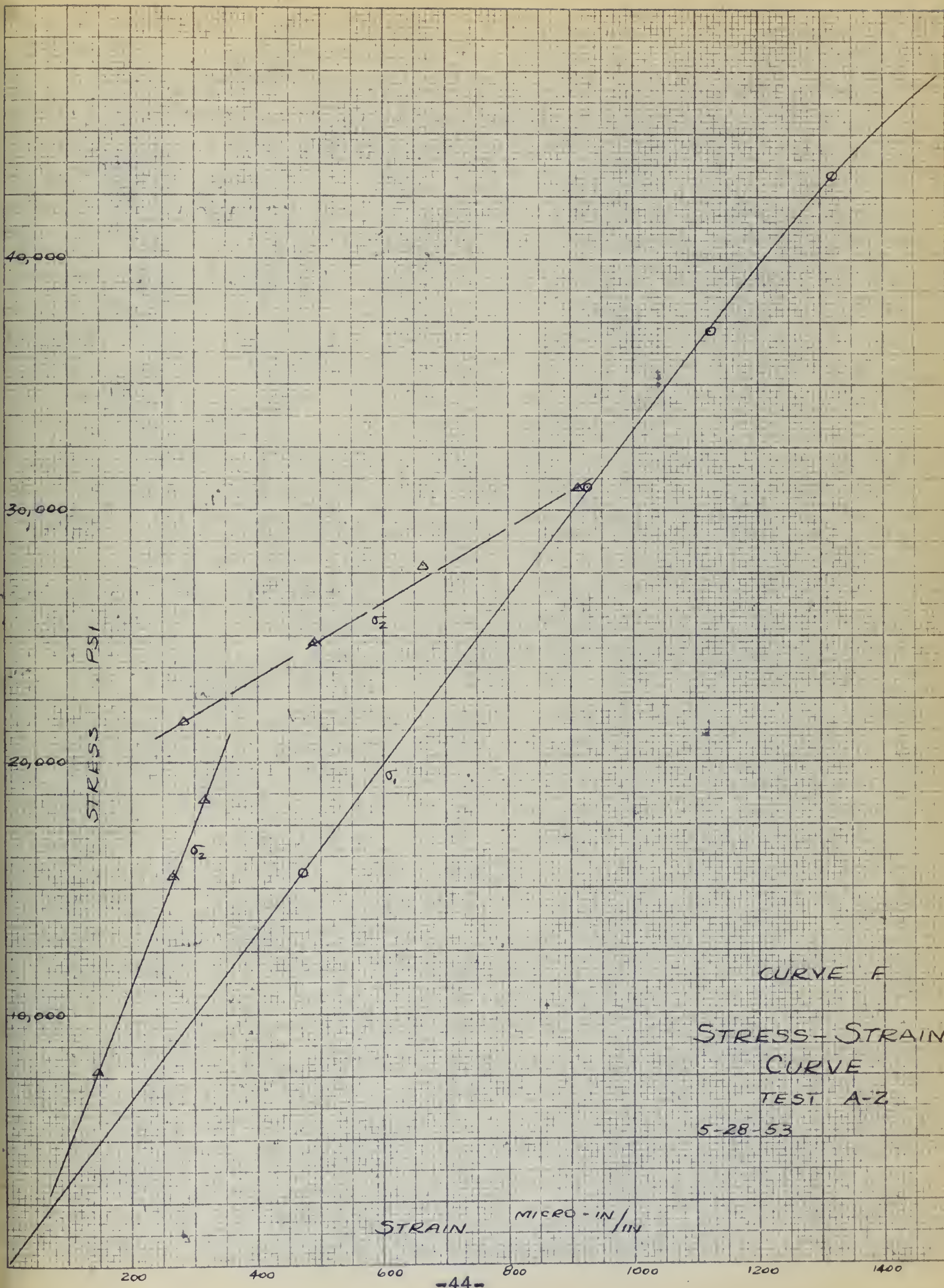
Date:5-28-53, Temperature; -31.4 degreesF, Stress Ratio: 1.65


40,000
30,000
20,000
10,000
STRESS PSI
σ_1
σ_2
CURVE E
STRESS-STRAIN
CURVE
TEST A-1
5-28-53
STRAIN MICRO IN/IN
200
400
600
800
1000
1200

Data for Test No. A-2:

σ_1	σ_2	Gage Reading	Elongation ϵ_1	Gage Reading	Elongation ϵ_2
0	0	6035	0	6665	0
15570	7735	6505	470	6805	140
30940	15470	7432	927	7070	265
37128	18564	8554	1122	7385	315
43316	21658	9874	1320	7665	490
49504	24752	off scale		8155	662
55692	27846			8817	662
61880	30940			9727	910
69444	34034				
69444	37128	specimen broke at this point.			

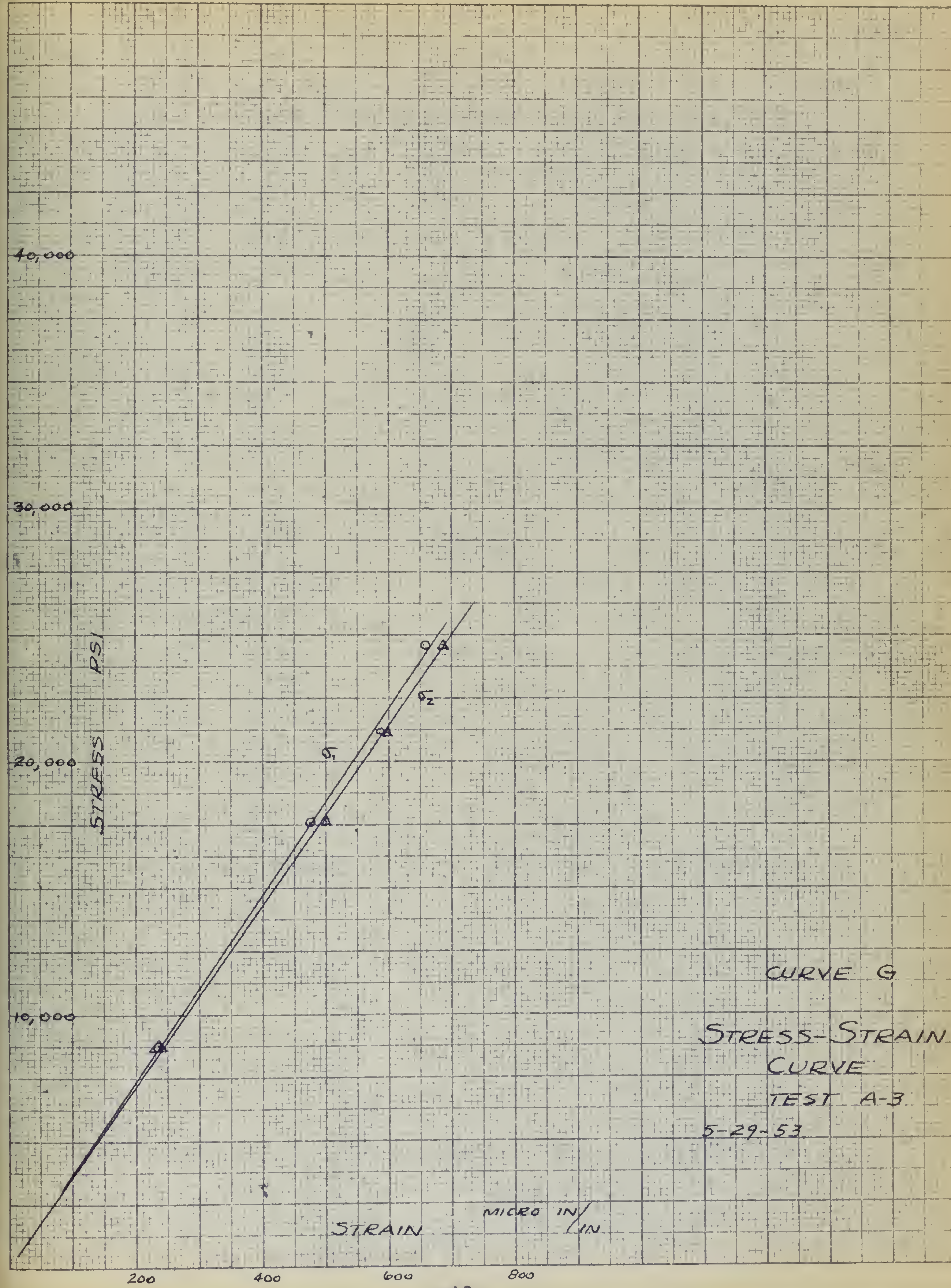
Date:5-28-53, temperature:-4 degreesF, Stress Ratio: 1.87


40,000
30,000
20,000
10,000
STRESS PSI
σ_2
σ_1
σ_2
200
400
600
800
1000
1200
1400
STRAIN MICRO-IN/IN
CURVE F
STRESS-STRAIN
CURVE
TEST A-Z
5-28-53

Data for Test No. A-3:

σ_1	σ_2	Gage Reading	ϵ_1 Elongation	Gage Reading	ϵ_2 Elongation
0	0	6245	0	5285	0
8810	8810	6480	235	5520	235
17620	17620	6720	475	5785	500
21144	21144	6830	585	5880	595
24668	24668	6900	655	5970	685
28192	28192				
31716	36716				
35240	35240				
38764	38764				
42288	42288				
45373	44931				
48371	44931 pipe broke at this point.				

Date:5-29-53: temp:-34 degreesF , Stress Ratio:1.075

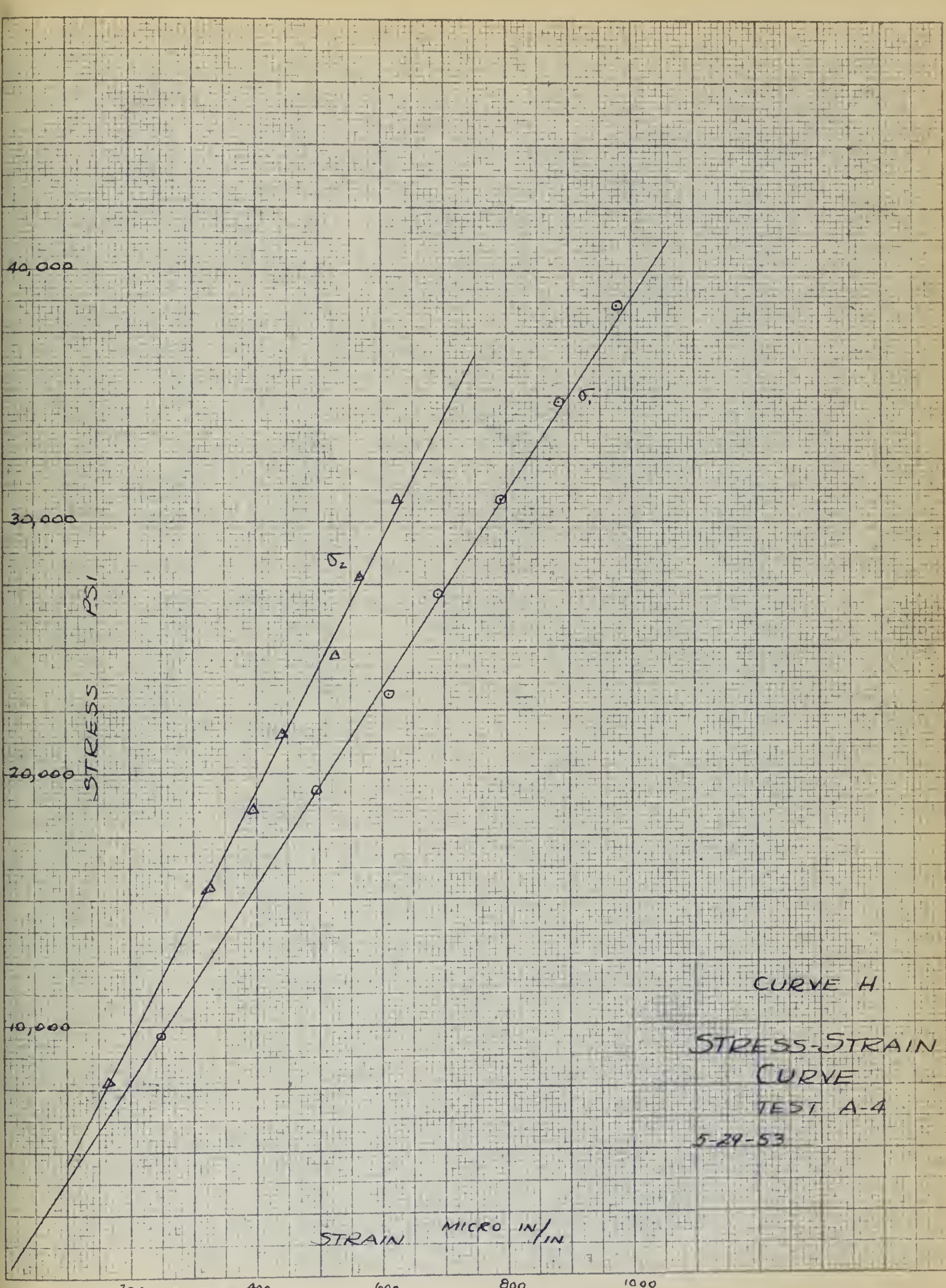


40,000
30,000
20,000
10,000
STRESS PSI
σ_1
σ_2
CURVE G
STRESS-STRAIN
CURVE
TEST A-3
5-29-53
STRAIN
MICRO IN/IN
200
400
600
800

Data for Test No. A-4:

σ_1	σ_2	Gage Reading	ϵ_1 Elongation	Gage Reading	ϵ_2 Elongation
0	0	6225	0	5605	0
9669	7735	6475	250	5770	165
19338	15470	6720	495	5930	325
23205	18564	6835	610	6000	395
27073	21658	6915	690	6045	440
30940	24752	7015	790	6130	525
34808	27846	7110	885-	6170	565
38675	30940	7200	975	6230	625
42543	34034				
46410	37128				
50278	40222				
54145	43316				
58013	46410				
61880	49504				
61880	49504				
65748	52598				
68098	55692	specimen broke at this point			

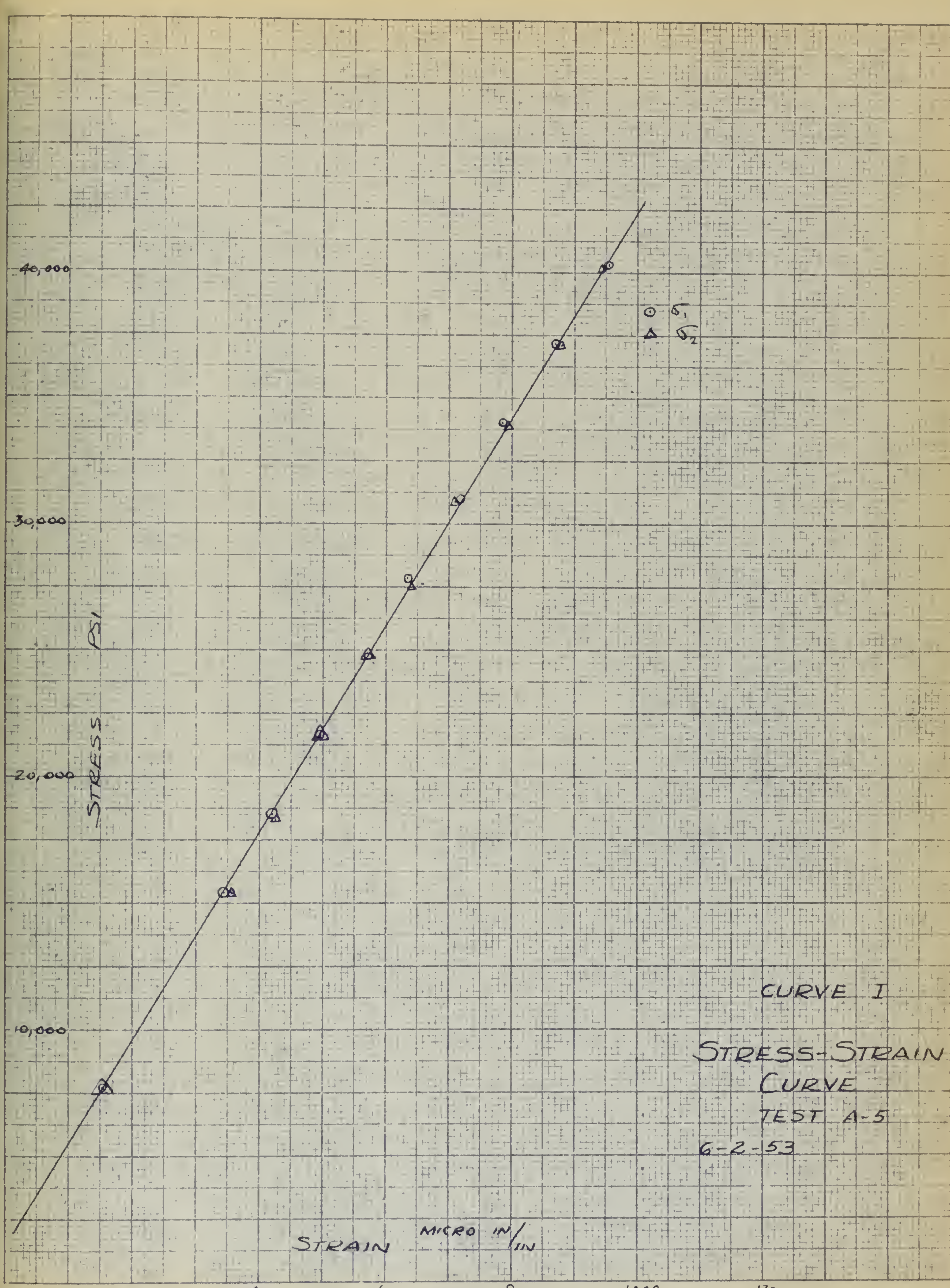
Date:5-29-53,Temperature: 3 dggreesF,Stress Ratio:1.22.


40,000
30,000
20,000
10,000
STRESS PSI
σ_2
σ_1
CURVE H
STRESS-STRAIN
CURVE
TEST A-4
5-29-53
STRAIN MICRO IN/IN
200
400
600
800
1000

Data for Test A-5:

σ_1	σ_2	Gage Reading	ϵ_1 Elongation	Gage Reading	ϵ_2 Elongation
0	0	6185	0	6080	0
7735	7735	6340	155	6235	155
15470	15470	6530	345	6435	355
18564	18564	6605	420	6500	420
21658	21658	6675	490	6575	495
247552	24753	6755	570	6650	570
27846	27846	6820	635	6715	635
30940	30940	6900	715	6790	710
34034	34034	6970	785	6870	790
37128	37128	7055	870	6955	875
40222	40222	7135	950	7025	945
43316	43316				
46410	46410				
49504	49504				
52598	52598				
55692	55692				
58786	58786				
61880	61880				
65665	61880	pipe broke at this point.			

Date:6-2-53,Temperature:-47.8 degreesF,Stress Ratio: 1.06 .


40,000
30,000
20,000
10,000
STRESS PSI
$\odot$ σ_1
Δ σ_2
CURVE I
STRESS-STRAIN CURVE
TEST A-5
6-2-53
STRAIN MICRO IN/IN
200
400
600
800
1000
1200

Data for Test No.A-6:

σ_1	σ_2	NO STRAIN GAUGES USED ON THIS SPECIMEN
0	0	
9669	7735	
19338	15470	
23205	18564	
27073	21658	
30940	24752	
34808	27846	
38675	30940	
42543	34034	
46410	37128	
50278	40222	
54145	43316	
58013	46410	
61880	49504	
65748	52598	
68789	55692	specimen broke at this point.

Date: 6-2-53, Temperature: -53.5 degreesF, StressRatio: 1.25

THERMOCOUPLE CALIBRATION FOR COPPER COPNIC

Reference Junction Temperature 32 F

TABLE A Millivolts at each 10 F

F	0	-10	-20	-30	-40	-50	-60	-70	-80	-90	-100
-300	-5.283	-5.378	-5.469	-5.556	-5.639						
-200	-4.110	-4.245	-4.376	-4.503	-4.626	-4.745	-4.861	-4.973	-5.081	-5.184	-5.283
-100	-2.560	-2.731	-2.899	-3.063	-3.223	-3.380	-3.533	-3.683	-3.829	-3.971	-4.110
0	-0.671	-0.874	-1.074	-1.272	-1.466	-1.657	-1.844	-2.028	-2.209	-2.386	-2.560
F	0	+10	+20	+30	+40	+50	+60	+70	+80	+90	+100
0	-0.671	-0.464	-0.255	-0.043	+0.172	0.389	0.609	0.832	1.057	1.285	1.516
100	1.516	1.750	1.987	2.226	2.467	2.711	2.957	3.206	3.457	3.710	3.966

TABLE B Degrees F at each 0.1 Millivolts

MV	0.0	-0.1	-0.2	-0.3	-0.4	-0.5	-0.6	-0.7	-0.8	-0.9	-1.0
-3	-126.2	-132.3	-138.5	-144.8	-151.2	-157.7	-164.3	-171.1	-178.0	-185.0	-192.1
-2	-68.5	-74.0	-79.5	-85.1	-90.8	-96.5	-102.3	-108.2	-114.1	-120.1	-126.2
-1	-16.3	-21.3	-26.3	-31.4	-36.6	-41.8	-47.0	-52.3	-57.6	-63.0	-68.5
0	32.0	27.3	22.6	17.9	13.1	8.3	+3.5	-1.4	-6.3	-11.3	-16.3
MV		+0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
1	32.0	36.7	41.3	45.9	50.5	55.1	59.6	64.1	68.6	73.1	77.5
2	77.5	81.9	86.3	90.7	95.0	99.3	103.6	107.9	112.1	116.3	120.5
3	120.5	124.7	128.9	133.1	137.3	141.4	145.5	149.6	154.6	157.7	161.7

Taken from "Tables of Thermocouple Characteristics-GET-1415" from the Apparatus Department , General Electric Corporation, Schenectady, New York.

TEMPERATURE CALCULATION DATA

Test #3 Room Temperature: 71.5 degrees F
Base Correction: .944 (from calibration chart)

Time in minutes	EMF in millivolts
00	0
05	-1.58
10	-1.88
15	-2.03
20	-2.04
25	-2.04
30	-2.04

Corrected temperature based on -1.10 is -21.3 deg F.

Test #4 Room Temperature: 71.5 deg F
Base Correction: .944

Time	EMF
00	0
05	-.95
10	-1.17
15	-1.30
20	-1.42
25	-1.51
30	-1.58
35	-1.60
40	-1.63
45	-1.64
50	-1.64
55	-1.66
00	-1.66

Corrected temperature based on -.52 is +7.3 deg F.

Test #A-1 Room Temperature: 66 deg F
Base Correction: .737

Time	EMF
00	0
05	-1.32
10	-1.60
15	-1.80
20	-1.94
25	-2.01
30	-2.01
35	-2.04
40	-2.04
45	-2.04

Corrected temperature based on -1.30 is -31.4 deg F

Test #A-2 Room Temperature: 70 deg F
Base Correction: .832

Time	EMF
00	0
05	-.40
10	-.73
15	-1.14
20	-1.37
25	-1.51
30	-1.59
35	-1.61
40	-1.61
45	-1.61

Corrected temperature based on -.78 is -5.4 deg F

Test #A-3 Room Temperature: 69 deg F
Base Correction: .807

Time	EMF
00	0
05	-.90
10	-1.22
15	-1.60
20	-1.72
25	-1.83
30	-1.91
35	-2.01
40	-2.05
45	-2.11
50	-2.15
55	-2.15
00	-2.15

Corrected temperature based on -1.34 is -33.4 deg F

Test #A-4 Room Temperature: 69 deg F
Base Correction: .807

Time	EMF
00	0
05	-.65
10	-.93
15	-1.08
20	-1.28
25	-1.35
30	-1.38
35	-1.40
40	-1.40

Corrected temperature based on -.60 is +3.5 deg F

Test #A-5 Room Temperature: 73.4 deg F
Base Correction: .908

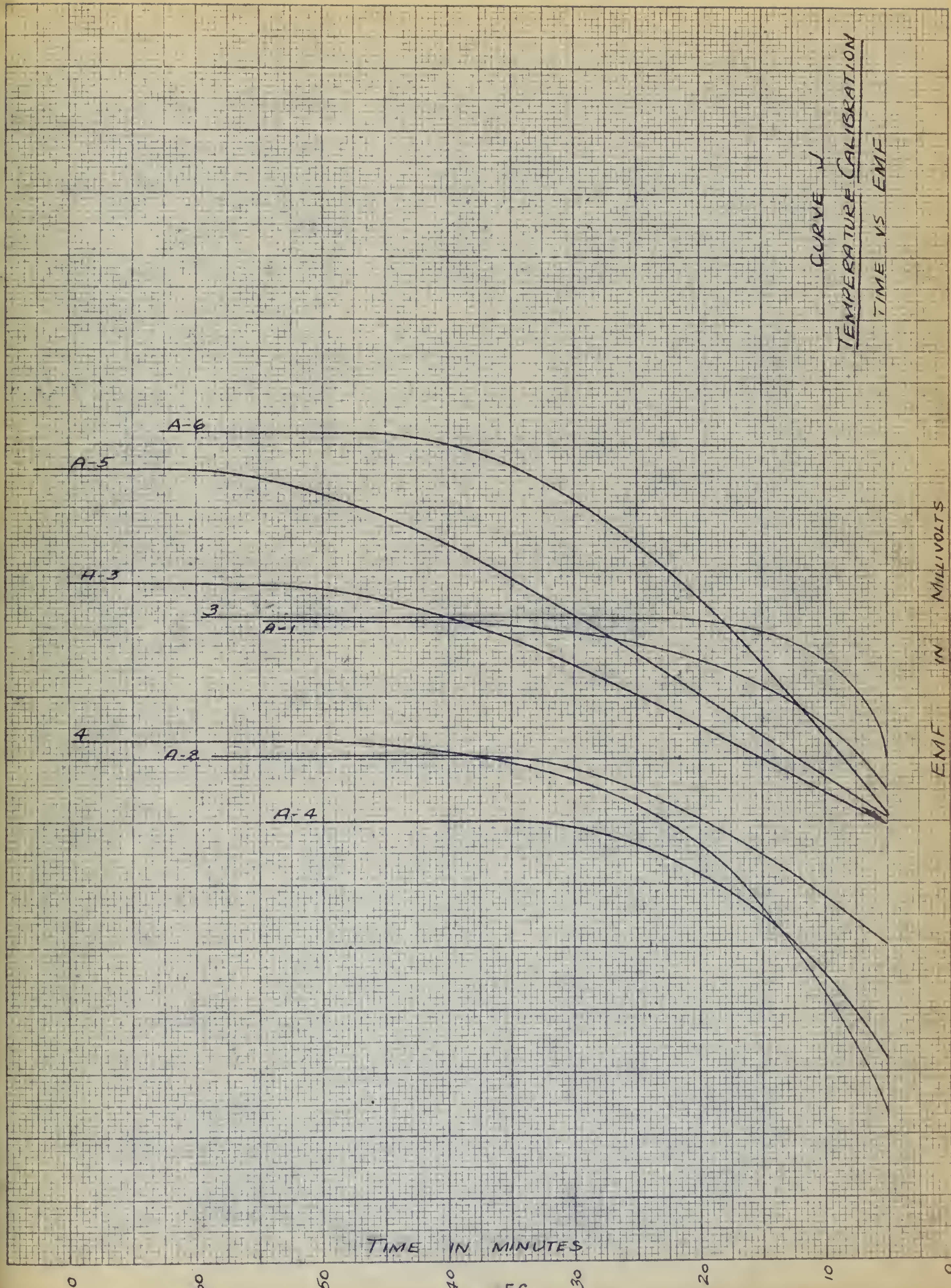
Time	EMF
00	0
05	-1.25
10	-1.53
15	-1.67
20	-1.82
25	-1.96
30	-2.07
35	-2.15
40	-2.22
45	-2.31
50	-2.37
55	-2.45
00	-2.46
05	-2.52
10	-2.52

Corrected temperature based on -1.61 is -47.5 deg F

Test #A-6 Room Temperature: 73.4 deg F
Base Correction: .908

Time	EMF
00	0
05	-1.20
10	-1.68
15	-1.95
20	-2.13
25	-2.28
30	-2.41
35	-2.47
40	-2.54
45	-2.63
50	-2.63
55	-2.63

Corrected temperature based on -1.72 is -53.3 deg F


CURVE V
TEMPERATURE CALIBRATION
TIME VS EMF
EMF IN MILLIVOLTS
TIME IN MINUTES
A-6
A-5
A-3
3
A-1
4
A-2
A-4
0
1.0
2.0
3.0
0
10
20
30
40
50
60
70

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